Soil Stabilization & Grouting for Microtunneling

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General Grouting

Grouting is the injection of pumpable materials into a soil or rock formation to change the physical characteristics of the formation.
General Grouting

- Grouting Can...
  - Add cohesion to granular soils
  - Reduce or offset settlements
  - Decrease permeability
  - Provide excavation support
  - Mitigate liquefaction potential
General Grouting

- **Grouting Can Prevent...**
  - Collapse of granular soils
  - Settlement under adjacent foundations
  - Utility damage
  - Tunnel day-lighting
Types of Grouting

- **Slurry Grout (Intrusion)**
- **Chemical Grout (Permeation)**
- **Compaction Grout (Displacement)**
- **Jet Grout (Erosion)**
- **Fracture Grout (Compensation)**

Courtesy of Hayward Baker Inc.
Ranges of Soils by Grouting Method

- **GRAVEL**
- **SAND**
- **SILT**
- **CLAY**

- **% Passing** vs **Sieve Size (mm)**

- **Sieve No.**: 1" 1/2" 4 10 40 100 200

- **Grouting Methods**: Cement Grouting, Chemical Grouting, Compaction Grouting, Jet Grouting, Fracture Grouting

Courtesy of Hayward Baker Inc.
Slurry Grouting is the intrusion under pressure of flowable particulate grouts into open cracks and voids and expanded fractures.
Slurry Grouting Applications

- Course Soil / Fractured Rock Stabilization
- Groundwater Control
- Annulus Filling / Contact Grouting
- Other Void Filling
Slurry Grouting Materials

- Portland Cement
- Water
- Clay (Bentonite)
- Additives and Stabilizers
- Sand and Bulk Fillers
- Microfine Cement
- Fly Ash
- Lime
Cement Groutability Ratio for Soil

\[ N_s = \frac{(D_{15}) \text{ Soil}}{(D_{85}) \text{ Grout}} \]

\( N_s > 11 \): Grouting consistently possible
\( N_s < 11 \): Grouting not possible

Types I and II Portland cement are suitable for soils coarser than 0.60 mm.

Type III Portland cement is suitable for soils coarser than 0.42 mm.
Cement Groutability Ratio for Rock

\[ N_R = \frac{\text{Width of fissure}}{(D_{95}) \text{ Grout}} \]

- \( N_R > 5 \): Grouting consistently possible
- \( N_R < 2 \): Grouting not possible
Chemical (Permeation) Grouting

**Structural Chemical Grouting** is the permeation of non cohesive soils with solution grouts to produce weak sandstone like masses to carry loads or increase stand-up time.

**Water Control Chemical Grouting** is the permeation of sands with fluid grouts to completely fill voids to reduce groundwater flow.
Chemical Grouting Applications

• Stabilize tunnel horizon

• Protect adjacent structures such as buildings, bridges, & utilities

• Control groundwater
Chemical Grouting

Cross Section of Individual Reusable Sleeve Port Grout Pipe

Courtesy of Hayward Baker Inc.
Chemical Grouting Design Steps

- Define grout pipe layout plan
Chemical Grouting Design Steps, cont’d

- Develop injection staging and sequencing plan
Chemical Grouting Installation Steps

- Drill and install Sleeve Port Grout Pipes
- Proportion grout, mix and inject into soil
- Make injection process measurements (QC)
- Perform post injection evaluation testing (QA)
Chemical Grout
Sleeve Port Grout Pipe Installation
Chemical Grout Mix Proportioning
Chemical Grout Injection Preparation
Chemical Grout Injection Monitoring
Chemically Grouted Tunnel Heading
Exposed Sleeve Port Grout Pipe in Chemically Grouted Soil
Compaction Grouting uses displacement to improve ground conditions. A very viscous (low-mobility), aggregate grout is pumped in stages, forming grout bulbs, which displace and densify the surrounding soils.

Courtesy of Hayward Baker Inc.
Typical Compaction Grout Consistency
Typical Compaction Grout Consistency
Compaction Grouting to Mitigate Tunnel Induced Settlement
Grout Casing Installation
Compaction Grout Batching Operations
Grouting and Surface Heave Monitoring
Jet Grouting is a versatile system used to create in situ engineered geometries of soil cement generally with limited required access.
Jet Grouting Process

1. Drilling
2. Starting jet grouting (Rising while rotating tube)
3. Completion of jet-grouting
Jet Grouting Equipment
Jet Grouting
Important Geotechnical and Structural Considerations

Jet grouting is effective across the widest range of soil types of any grouting system, including silts and some clays.

Because it is an erosion based system, soil erodibility plays a major role in predicting geometry, quality and production.

Cohesionless soils (sands and gravels) are typically more erodable than cohesive soils (silts and clays).
Jet Grouting Applications
Jet Grout
Docking Block for TBM

Jet Grouting was used to stabilize soil around a TBM in order to perform unanticipated maintenance in front of the cutter head at a depth of 120 feet and 80 feet below the water table.
Jet Grout
TBM Docking Block Stratigraphy
Jet Grout
TBM Docking Block Design
Jet Grouting Operations
Jet Grout Material in Front of Cutter Head
Jet Grout Material in Front of Cutter Head
Jet Grouting
Shaft Bottom Seal & Break In/Out Blocks

Jet Grouting was used to seal the bottom of multiple tunnel shafts and provide stabilize soil zones to aid in TBM launch and recovery up to 60 feet below the water table.
Jet Grouting
Shaft Bottom Seal & Break In/Out Blocks
Jet Grouting
Exposed Shaft Bottom Seal
Jet Grouting
Exposed Shaft Bottom Seal
Compensation Grouting

**Compensation Grouting**, is the injection and intentional hydro fracturing with slurry grout within the soil horizon between the foundation to be controlled and the mined tunnel causing the settlement.

Repetitive introduction of slurry grout induces fractures, thereby causing an expansion to take place counteracting the settlement that occurs or producing a controlled heave of the foundation. In addition, multiple injections and multiple levels of fractures create a complementary reinforcement zone.
Compensation Grouting Involves:

- Installing grout injection tubes in a predetermined pattern
- Monitoring movements by precise real time computer data acquisition through leveling or robotic survey systems
- Injection of grout into sleeve ports with careful process control to induce settlement compensating movements
Compensation Grout Exhumed Hydro Fracture
Subway Tunnel Construction

- Compensation Grouting is specified to mitigate anticipated surface settlements during initial twin tunnel mining operations with a curved alignment and relatively shallow cover.

- Horizontal Directional Drilling methods were used to place sleeve port grout pipe array.

- Grout injection carried out in conjunction with computer controlled and monitored robotic total stations survey system.
Subway Tunnel Construction
Compensation Grouting Plan
Grout Pipe Installation by Horizontal Directional Drilling
Grout Pipe Installation
Total Station and Prism Installation
Secondary Robotic Total Station Location
Robotic Total Station
Computer Settlement Monitoring
Deep Soil Mixing is the in situ mechanical mixing of a cement grout with soil to produce a variety of engineered geometries and soil properties to suit the application.
Deep Soil Mixing Applications

- Increased Bearing Capacity
- Settlement Reduction
- Support of Excavation
- Liquefaction Mitigation
- Seepage Control
Deep Soil Mixing
Deep Soil Mix Columns
Deep Soil Mixing
Batch Plant & Soil Mixing Rig
Deep Soil Mixed Wall Plan Layout

- Wide Flange Soldier Beam
- Soil-Cement Column

4'-0" O.C. TYP.
36" TYP.
Deep Soil Mixed Wall
Deep Soil Mixed Underpass
Deep Soil Mixed Shaft Wall
Questions?

Thank You!
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GROUND IMPROVEMENT FOR
MICROTUNNELING/PIPE JACKING APPLICATIONS

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INTRODUCTION

Ground improvement applications for microtunneling and pipe jacking projects have been shown to provide many benefits during both the construction phase and to enhance the long-term performance of these projects. This paper presents a synopsis of the many available ground improvement techniques followed by a description of the specific applications, case histories, and finally planning and design considerations. The focus of this paper is to provide the reader with “hands-on” knowledge to apply the techniques to subsequent project design and construction. Ground improvement applications presented include the following:

- Long-term support of a microtunneled pipeline constructed in compressible soils.
- Breaking in and out of shafts.
- Shaft bottom seals and perimeter seals to avoid the need for dewatering.
- Post construction grouting to eliminate the occurrence of ground settlement.
- Grouting at material interfaces to aid in controlling line and grade.
- Seismic stabilization of slopes and embankments to protect the microtunneled pipe during earthquakes.
- Seismic stabilization of liquefiable soils to reduce seismic induced settlement.
- Conditioning of the ground through the face of the machine to control ground loss.

The paper will first address and describe the various techniques and appropriate soil applications; this will be followed by a discussion of applications with schematics and approach recommendations; specific examples are then used to show where the applications have been successfully used with microtunneling and pipe jacking; finally rough guidelines for planning, cost estimating, and specifying the ground improvement applications are presented.
GROUND IMPROVEMENT TECHNIQUES

There exist many different techniques for improving various characteristics of soil. A wide range of grouting techniques (slurry, permeation, compaction, jet, and fracture grouting) can be used to reduce permeability, densify, stabilize, and / or solidify the ground. Each type of grouting has a different purpose, uses different material, different pumping pressures and equipment, and produces different end result (Welsh, 1992). Figure 1 illustrates the different forms of grouting available. Soil mixing, like some grouting techniques, can solidify the ground to a predictable level of performance. Dewatering and ground freezing both modify the groundwater regime to effect changes in the surrounding soils. The installation of stone columns, by the vibro-floatation technique, can mitigate liquefaction potential and improve bearing capacity through reinforcement and densification.

![Figure 1. Grouting Techniques](image)

**Slurry Grouting**

Slurry Grouting is the intrusion, under pressure, of flowable particulate grout into open cracks, voids, or expanded fractures. This is the oldest and most familiar form of grouting. The most common slurry grout is a colloidal mixture of water and portland cement. Other common materials in slurry grouts may include sand, fly ash, micro-fine cements, and various concrete admixtures. Slurry grouting is primarily used to consolidate and reduce groundwater flows through fractured rock masses and coarse sandy gravels.
Permeation Grouting

Permeation grouting or chemical grouting, as it is more commonly referred to, is the injection of low viscosity solution or fluid grouts to permeate the pore spaces in granular soils. The most common chemical grout material is sodium silicate based solution which typically use an organic reactant to attain predictable gel times. Chemical grouting can produce rock-like masses to carry loads or enhance stability when used for structural purposes. Chemical grouting is extensively used in soft ground tunneling to prevent excessive ground loss. Chemical grouts are also effective waterproofing agents. Chemical grouts when applied to completely fill voids may reduce or control groundwater flows.

Compaction Grouting

Compaction grouting is the injection, under relatively high pressure, of a very stiff, low slump mortar-like grout to displace and compact soils in place. Compaction grout usually consists of a mixture of silty sand, portland cement, and water sufficient to achieve a slump less than 75mm (3 inches). When low slump compaction grout is injected into granular soils, bulbs of grout amass, displacing and thus densifying the surrounding loose soils. This technique is ideal for limiting structural or surface settlements.

Jet Grouting

Jet grouting is a Ground modification system used to create in situ cemented geometries of soil, otherwise known as Soilcrete\textsuperscript{sm}. Through the use of a specially modified rotary drill rig, a high velocity fluid is injected to erode and mix grout materials in situ with the soil to produce stabilized masses of high strength and / or low permeability. Initially, jet grouting was utilized mainly for excavation support and underpinning (Burke, et al. 1989). More recently, it has been used to prevent groundwater migration as vertical and horizontal barriers (Welsh and Burke, 1995). There are three traditional jet grout systems. Figure 2 shows the three jet grouting techniques. Selection of the most appropriate system is generally a function of the in situ soil, the application, and the physical characteristics of the Soilcrete required for that application.
The Single Rod Jet Grouting (Soilcrete S) utilizes neat cement grout pumped through the drill rod, which exits the horizontal nozzle(s) in the monitor at a high velocity [approximately 200m/sec (650 ft/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. However, it is particularly well suited to horizontal drilling applications thereby having greater accuracy for drilling at greater depths. The Double Rod Jet Grouting system (Soilcrete D) employs a two-phase internal rod for the separate supply of grout and air down to different, concentric nozzles on the monitor. As with the Soilcrete S, grout is used for eroding and mixing with the soil. The addition of air shrouds the grout jet, increasing erosion efficiency, thereby enhancing the effective range of the system. The double rod system is more effective in cohesive soils than the single rod system. For Triple Rod Jet Grouting (Soilcrete T), 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 nozzles below the erosion jet. This somewhat 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.

Jet grouting is a versatile and valuable tool for soil stabilization, underpinning, excavation support and groundwater control in the widest range of soil types. It is particularly well suited for protection of sensitive structures or where access is difficult or limited.

Fracture Grouting

Fracture grouting or compensation grouting is an advanced form of highly controlled slurry grouting. Through the use of state-of-the-art real time settlement monitoring, coupled with carefully controlled multi-port grout injection, it is possible to intentionally fracture a cohesive soil and induce consolidation and heave to control excavation induced settlement, i.e.
compensate, for sensitive overlying structures. It is now feasible to control movements to millimeter tolerances through the use of fracture grouting.

Soil Mixing

Soil mixing is a ground improvement technique combining the use of a mechanical mixing tool(s) with the simultaneous injection of a dry or wet stabilizing agent(s) to produce an in situ mass of treated soil. Various multi-auger machines have been used to create walls for both excavation support and groundwater control applications. Larger diameter single axis mixing tools have been used for soil stabilization mass treatment.

Stone Columns

Stone columns, also known as vibro-flotation, are a ground improvement method often used beneath structures and sometimes beneath embankments. Stone columns have been considered a means to densify and/or improve the strength characteristics of potentially liquefiable soils. The typical process employed in stone column construction consists of first lowering a large, crane-mounted vibratory probe into the ground. The probe generally easily penetrates down through the soils due to the combined effects of its own weight, vibrations, and high pressure air or water jetting. Once the probe reaches the bottom elevation of treatment, stone is tremmied to the bottom of the hole. The probe is gradually and repeatedly raised and lowered, typically over about a 4-foot interval, to vibrate and compact the stone to construct a column. This sequence of adding stone to the system, and raising and lowering the probe through a given interval, is repeated all the way to the top of the hole. Multiple rows of stone columns are constructed in order to provide a sufficient aerial extent of treated soil.

Ground Freezing

Ground freezing is the use of refrigeration to convert in situ pore-water to ice. The ice then acts as a cement or glue, bonding together adjacent particles of soil or blocks of rock to increase their combined strength and make them impervious. Ground freezing applications include temporary support of excavation, groundwater control, and soil stabilization. The basic principle of ground freezing is to circulate a cold medium (a refrigerated brine solution or liquid nitrogen) through a suitable pipe system, which cools the strata and thus converts the in-situ pore water to ice. The ice so formed bonds adjacent soil particles together and forms an impermeable structure with increased strength characteristics. Careful attention must be given to potential ground heave due to freezing.
Dewatering

Dewatering involves the removal of water from the ground to lower the groundwater within of around the microtunnel or shaft(s). This is commonly performed by a series of wells installed in close proximity to the work that are pumped continuously throughout the construction operation. Dewatering can provide an increase in a granular soil’s effective stress and reduction of potential flowing ground or ‘quick’ conditions. Care must be exercised when dewatering to ensure that there are no detrimental effects to adjacent structures, or that offsite waterborn contaminants are not transported or intercepted.

GROUND IMPROVEMENT APPLICATIONS

There are at least a dozen possible applications where ground improvement can be used to improve the constructibility and performance of microtunneled/pipe jacking installations. Several are presented below. Many of these have been developed with no prior precedence and numerous other applications are possible with a little creative thinking. The following applications are discussed in more detail below.

- Breaking in and out of shafts.
- Improving thrust block resistance.
- Shaft bottom seals and perimeter seals to avoid the need for dewatering.
- Post construction grouting to eliminate ground settlement.
- Grouting at material interfaces to aid in controlling line and grade.
- Conditioning of the ground through the face of the machine.
- Seismic stabilization of soils, slopes, and embankments for earthquake protection of microtunneled pipeline.
- Long-term support of pipelines constructed in compressible soils.

Breaking In and Out of Shafts

Breaking out of the shaft requires the shoring to be cut and in the case of steel shoring exposing the ground just prior to pushing the microtunneling machine through the opening. Breaking into the shaft requires the same process except that the machine can be pushed up against the shoring just prior to making the cut. In the case of breaking out, and to a lesser extent, breaking in lends itself to the potential for unstable soil primarily below the groundwater in cohesionless soils which have the potential to flow. Several techniques are available to improve the ground prior to cutting the shoring including both dewatering and grouting. Dewatering wells can be placed right at the opening do reduce the groundwater pressure. This can be sufficient in wet clay or dense slightly cemented sand. In other less stable soils, alternative treatment with grouting may be necessary. Specific grouting techniques can include permeation grouting or jet grouting.
Improving Thrust Block Resistance

For long drives in poor soil conditions or at shallow depths, it is quite common for there to be insufficient soil resistance to carry the jacking loads without excessive deformation of the thrust block and shaft wall. The soils can be improved with dewatering and ground improvement to increase their capacity. Dewatering alone can give extra strength to granular soils as their strength is proportional to the effective stress which is increased in a dry state versus a saturated condition. Ground improvement methods such as compaction grouting, permeation grouting, and jet grouting can be used to improve the soils and add extra jacking load capacity. Figure 5 shows a shaft thrust block which was improved with compaction grouting behind the thrust wall for support.
Figure 5. Thrust Block Improved by Compaction Grouting Outside the Shoring

Shaft Bottom and Perimeter Seals

In order to construct dry shafts in permeable soils below the groundwater table without dewatering either a water tight shoring system is required, or ground improvement may be used to create a cutoff to the groundwater. The cutoff can be done around the perimeter of the shoring and along the bottom of the shaft. Either permeation grouting or jet grouting can provide the cutoff. With these cutoffs in place, less than watertight shoring can then be used to construct the shaft. Figure 6 shows a schematic of a layout to construct a bottom seal for a shaft where a manhole was to be subsequently placed.

Figure 6. Jet Grout Bottom Seal and Manhole Support Detail. (Honolulu, 1995)
Surface Settlement Control

While microtunneling provides excellent face control to minimize surface ground settlement, surface settlement is always possible especially if a more traditional small tunneling machines with less optimum face control is used. As with many large diameter tunneling project, surface settlement can be mitigated by using compaction grouting techniques from the surface right behind the tunneling machine. Fracture grouting is an alternative to compaction grouting where increased accuracy or highly sensitive structures are involved. Typically compaction grout pipes are installed in advance of the tunneling operation. Then as the tunneling machine passes by the location compaction grout is injected to account for any lost ground and reduce the potential for surface settlement. The ground can be monitored for surface settlement using traditional surface control points or down hole extensometers or “Sondex” type measuring devices. If settlement is detected the grout can be immediately injected. Figures 7 and 8 show a compaction grout settlement control schematic and an actual set of grout pipes installed and ready for the tunneling machine to pass.

Figures 7 & 8. Schematic Showing Grouting for Settlement Control (Welsh, 1993) and Grout Pipes at an Exit Shaft Ready for Compaction Grouting

Grouting at Material Interfaces for Line and Grade Control

For gravity open channel flow type sewer or storm drain installations, grade control can be especially important. In many cases several soil types are encountered and quite often these have distinctly different properties where softer soils overly stiffer soils. Under this scenario it may be difficult to drive the tunnel from the soft soil into the hard soil without it deflecting off the hard soil layer and losing the grade control. Several options exist, such as lowering the tunnel alignment, raising the tunnel alignment, or driving the tunnel at the preferred location from the hard soil into the softer soil. If these options are not feasible or if the tunnel skips in and out of the interface, grouting can be done to stiffen up the softer soil so that it has properties more similar to the harder soil. Figure 9 shows a geologic profile where jet grouting was used to stiffen the soft soil and provide a smooth interface into the hard soil deposits.
Conditioning of the Ground Through the Face of the Machine.

The ground can be conditioned through the face of a microtunneling machine with proper slurry control through the muck transportation system. The conditioning is done with polymer type admixtures to the slurry system and provides a number of possible benefits including:

- Stabilizing sandy soils so that it has less potential to flow around the machine thus creating a more stable opening with less friction on the pipe as it is jacked.
- Adding in breaking down stiff clay clasts which can be difficult to break and convey through the cutterhead openings and into the slurry system.

Stabilization of Unstable Slopes and Liquefiable Soils

Weak soils, especially during seismic events, can become unstable and cause large ground displacements, which will likely disrupt the pipeline, no matter how it is installed. Under certain circumstances these situations can be eliminated or reduced with applicable ground improvement techniques. The appropriate techniques include stone columns, compaction grouting, permeation grouting, and jet grouting depending on the soil conditions. The stabilization is best done in advance of the microtunneling/pipe jacking so that it does not damage the pipeline during the ground improvement phase. Figure 10 shows a schematic cross section of an application where an embankment was stabilized using stone columns and compaction grouting to prevent lateral and vertical movement as a result of liquefaction during a moderate to strong earthquake.
Long-term Pipeline Support

Pipelines constructed in under consolidated soils can experience settlement long after they are constructed as the soil naturally settles under its own self weight. Under this circumstance pipeline settlement can occur no matter what tunneling technique is used. Typically, either the settlement is allowed to occur and the problem is handled by way of long-term maintenance or the pipeline is pile supported and constructed using open trench techniques. Ground improvement can be substituted for pile support so that the pipeline can be constructed through the improved ground using microtunneling/pipe jacking techniques. The ground improvement techniques can include permeation grouting and jet grouting with applications for stone columns or compaction grouting being more limited. The ground improvement is usually carried down to firm soil in a series of alternating or continuous line of improved soil along the pipeline alignment. Figure 11 shows a typical schematic where jet grouting was used to provide this form of long-term support.
CASE HISTORIES

Nimitz Highway Relief Sewer

The Nimitz Highway Relief Sewer project demonstrates one of the largest known overall uses of ground improvement techniques applied to date in the United States. Jet grouting was used to stabilize approximately 3,000 feet of microtunneled pipeline along with 12 shafts and manhole foundations in Honolulu, Hawaii. The project included the following elements:

- Support of the microtunneled pipeline using a series of jet grout constructed columns to provide presupport for a 54-inch reinforced concrete pipe to be installed by microtunneling. Figure 11 shows a schematic.
- Long-term support of manholes constructed within shafts using selectively placed jet grout columns drilled into underling strong material.
- Jet grout seals for breaking into and out of shafts.
- Jet grout seals constructed at the base of and at open joints of sheetpile supported shafts eliminating the need for external dewatering.

North Metro Interceptor

The North Metro Interceptor project in San Diego used compaction grouting and stone columns to stabilize soils for a variety of reasons to aid in both construction support and for long term performance. One segment of the project, which included approximately 3,000 feet of 108-inch
reinforced concrete pipe and three heavily loaded structures, was constructed through soft soils with pipe jacking techniques. The project included the following elements:

- Stone column reinforcement of heavily loaded junction structure and conflict structures foundations.
- Compaction grout densification of embankment foundation soils for improved resistance to seismically induced liquefaction related displacement.
- Compaction grout stabilization of soils above the tunnel boring machine for surface settlement control when breaking out of the shaft.
- Compaction grout stabilization of soils behind the thrust block which were loosened during the shoring installation process.

Duwamish River Crossing

The Duwamish River Crossing in Seattle, Washington used an impressive ground freezing system to provide support for shafts approximately 80 feet deep used to jack a 9-foot diameter pipe across this waterway. Ground freezing using a brine solution was injected around the jacking and receiving pits in a circular pattern with excavation taking place within the ring of freeze pipes. A concrete collar poured at the surface provided the only additional support to the frozen soil during the entire construction process. On the receiving shaft side, higher than expected groundwater velocities required liquid nitrogen injection and permeation grouting to get final closure of the freeze wall. Figure 12 shows a picture looking down the jacking shaft.

Figure 12. Photograph Looking Down Frozen Shaft with Ice for Support.

West Bank Interceptor Relief Sewer
The West Bank Interceptor Relief Sewer project in Dallas, Texas used jet grouting to provide soil stabilization along two separate sections of a microtunnel alignment. The Soilcrete allowed the contractor to utilize a rock tunnel machine across a variety of mixed face conditions, including a transition from bedrock into a clay strata. The jet grouting modified the overlying soils to increase unconfined compressive strength and control groundwater in otherwise, potentially unstable material. Protection was also provided for several critical existing utilities crossing the alignment. Figure 13 illustrates the installation of the clay bedrock interface stabilization.

![Figure 13. Schematic of Jet Grout Soft Ground Stabilization at Soil/Rock Interface](image)

**Saint Clair River Tunnel**

The Saint Clair River Tunnel project required a soft ground tunnel to be driven directly beneath a settlement sensitive research facility built on shallow spread footings (Droof, et al, 1995). Fracture grouting was used to maintain the grade of the existing three-story building throughout tunnel construction.
DESIGN GUIDELINES

Planning

Planning ground improvement applications requires two fundamental considerations as follows:

- Are the ground conditions appropriately characterized to select the appropriate method of improvement?
- Are the ground improvement requirements directed towards short-term construction related issues or long-term performance related criteria?

The ground conditions in the areas of concern have to be accurately characterized with exploratory borings and laboratory testing. The most important parameters include the soil classifications with grain size analysis, density, and moisture content of key importance. Information from the exploratory borings should include locations of soil changes, groundwater levels, and Standard Penetration Test equivalent blow counts. This information is necessary to select the most appropriate methods and to provide a basis for evaluating the level of improvement achieved following the ground improvement application. It is important to recognize that more soil information than typical is needed when ground improvement is expected to be implemented.

Selection of the appropriate ground improvement application will not only depend on the ground conditions but also on the application requirements as discussed in the previous section. All appropriate approaches should be considered and the most appropriate cost affective methods should be selected. Where the ground improvement is meant to provide short-term construction applications, less specific requirements need to be developed initially. For construction applications, initial consideration need only be given to an evaluation of the appropriate methods, costs, and specification requirements. Final selection, design, and implementation is left to the Contractor. Performance verification by the Owner may only include key items such as monitoring of ground settlement, stability at the face of the tunneling machine, etc. On the other hand, where the ground improvement is meant for long-term performance, the designer needs to make a more detailed assessment of the preferred technique with specific requirements included in the specifications. During construction more consideration has to be given to verifying that the ground improvement was done in accordance with the specified requirements by observing, monitoring, lab testing, and field testing, if appropriate to the application. In general, it should be recognized that long-term applications require more involvement from the design engineer than short-term construction related applications do.
Cost Estimating

The large number of techniques and numerous potential applications make it difficult to present a comprehensive guide to the costs related to each technique. One should consider the following factors, at a minimum, which can significantly impact the cost of performing any ground improvement technique.

- Existing soil conditions (classification, density, gradation, moisture content, etc.)
- Groundwater conditions (elevation, flow, perched water, potential contaminants, etc.)
- Purpose(s) of required improvement and suitability of improvement criteria.
- Site constraints (access restrictions, existing facilities, geometry requirements, etc.)

Given the above information, it would be appropriate to contact an experienced practitioner of the ground improvement technique(s) to obtain a more definitive budgetary cost estimate for a specific project or application.

Specifying and Contracting

Specification requirements will depend on the following:

- Is the ground improvement for a long-term or short-term application?
- Is the specification to be written as a “methods specification” or “performance specification”?

In general ground improvement specifications for short-term applications will be written as a performance based specification and ground improvement for long-term applications will be written as either a methods based specification or a performance specification. For long-term applications a performance based specification is most appropriate where a post improvement testing/monitoring program can be implemented to verify compliance with the performance requirements. The compliance verification is most commonly used when the ground improvement is intended to densify granular soils and the blow count or cone penetrometer tip resistance can be used for compliance verification. Assuming that some form of verification test is available, performance verification provides an excellent means of specifying the work, otherwise the methods specification may be a more appropriate application.

A methods specification is one where the Contractor is told how to execute the work. The owner is responsible for how the completed work performs. For example, a methods specification would dictate such things as the method or technique to be employed, type and quality of materials (cement/chemicals), type and size of equipment to use, acceptable drilling methods, minimum and maximum injection pressures, refusal criteria, etc. Additionally, the contract
drawings would prescribe such other requirements as the diameter, spacing, and depth of grout holes, grout geometry and layout, grouting sequence, etc.

A performance specification, on the other hand, directs how the finished product is to perform. The contractor, not the owner, is responsible to ensure that all of the specified performance criteria are met for the finished product. The contractor is free to use any technique he chooses to achieve the performance requirements. (Henn, 1996)

Regardless of the approach selected (performance vs. method), it may be desirable to prequalify the ground improvement contractor so that the owner has more control over the selection process. Specific attention should be given to technical and financial qualification and a careful check of representative references attesting to previous experience. This can lead to a higher quality product with less potential for claims.

Quality Control and Monitoring

A good quality control program helps insure the technical requirements of the ground improvement are met and also adds to the overall success of the project. The design must be adequate to meet the project engineering requirements while remaining reasonable and sufficiently flexible from a constructibility standpoint. This can be aided by retaining an experienced construction engineer during the early stages of the design. Another aspect of the quality control program is to write quality into the specifications. This can be accomplished by requiring equipment, methods, and materials that are commonly used, have a good record of success, and are readily available. Innovative applications may be considered commensurate with the size, location, and sophistication of the proposed application.

The field quality control and monitoring program is made up of several components including an experienced contractor, experienced inspector, preconstruction planning, preconstruction checklist, obtaining and verifying material and equipment certifications, developing and maintaining drilling and grouting records, and performing production testing and post grout verification of improved soils using drilling or cone penetrometer tests.

Inspection reports are the primary documents used as activity records. Reports should record the drilling activities and the grout mixing and injection operations. These are supplemented by use of an inspector’s diary. Drilling reports should be kept for each grout hole indicating such items as hole location, diameter, depth, spacing, etc. Grouting reports contain items such as grout mix used, batching information, injection pressures, grout quantity, etc.

Testing includes laboratory testing, field testing, and performance testing. Laboratory tests are used to provide post grout verification of chemical and physical properties of the grout materials. Field testing is done to check the quality of the grout just prior to injection using tests for density,
specific gravity, viscosity, and bleeding. Performance testing can be done by drilling and sampling, standard penetration blow counts, and cone penetrometer testing. In some cases a test section is performed in advance of the production work to verify that all selected parameters are adequate or to make revisions prior to production work. (Henn, 1996)

CLOSING

Ground improvement adds another dimension to microtunneling. The techniques presented can provide both economical and technical performance benefits. Microtunneling applications that otherwise might be extremely risky or not feasible can now be realistically accomplished with the addition of ground improvement. With up front planning, detailed evaluations and investigations, appropriate applications, and proper specifying/contracting practices, the results can be astonishing.

REFERENCES