2.4 JET GROUTING
INTRODUCTION
Jet grouting as a soil improvement technique is currently utilized throughout the world. From its conception in Japan in 1973 (Yahiro and Yoshida 1973) its use has spread, first to Europe, then to South and North America, the Far East, Asia, and Africa. The system of using hydraulic energy to erode the ground is now being extended to other applications and is being used in conjunction with other techniques for better control of the improved soils. Jet grouting offers a unique degree of design flexibility for a wide range of soil conditions and for a broad range of applications. These include working in and around sensitive structures where property and personnel safety are imperative.

Jet grouting can be defined as a method based on the introduction of hydraulic (sometimes combined with pneumatic) energy in order to erode soil and mix/replace the eroded material with an engineered grout to form a solidified in situ element known as Soilcrete. The elements are most often interconnected to provide underpinning to structures, excavation support, groundwater control, or in soil stabilization for a variety of civil and environmental applications.

Prior to Soil Improvement - A Ten Year Update (Welsh 1987), only a very few jet grouting projects were completed in the United States (Langbehn 1986. Andromalos and Gazaway 1986). Indeed, the conference itself included no U.S. jet grouting case histories. Since that time, well over 150 projects have successfully utilized jet grouting methods. Many of these projects have been documented. A selection of readily available North American publications is provided in a chronological bibliography at the conclusion of this section of the report, the better to illustrate the progress of the jet grouting timeline since 1987. Many more publications exist internationally.

Table 24-1 below places those U.S. publications into the five broad application categories previously discussed. This serves as very substantial support from the engineering and construction community that jet grouting offers a system suitable to many applications and a wide variety of soil types and stratigraphy.

![Fig. 2.4-1. Jet grouting systems.](image-url)
FUNDAMENTAL CONCEPTS

As shown in Fig 24-1, there are three basic styles of jet grouting (Burke and Mello 1991). There has been much discussion over the years related to jet grouting being a high pressure grouting system. This is not at all correct and warrants review. For each system, in situ erosion of soils occurs by impact energy from a high velocity fluid stream(s). Note that the velocity of the fluid is created by pumping pressure forcing it through a small nozzle(s). The distribution of fluids injected into the ground is through a "monitor" located at the end of the drill string, but just above the drill bit. The drill bit is sized larger than the drill string and monitor, permitting return of slurry up the annulus between the drill string and the borehole wall at a rate sufficient to carry soil cuttings and to ease ground penetration. If any pressure results during the erosion process of jet grouting, it is immediately relieved via the drill annulus.

Table 24-1 Jet grouting applications

<table>
<thead>
<tr>
<th>Application</th>
<th>Chronological Bibliography Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation Support/Underpinning</td>
<td>4, 5, 6, 7, 9, 12, 14, 15, 16, 17, 20, 21, 28, 29, 31, 34, 36, 37, 39, 43, 44, 46</td>
</tr>
<tr>
<td>Groundwater Control</td>
<td>4, 5, 11, 17, 19, 25, 28, 30, 34, 35, 37, 39, 40, 42, 43</td>
</tr>
<tr>
<td>Tunnel/Ground Stabilization</td>
<td>1, 3, 4, 5, 8, 13, 15, 26, 29, 34, 37, 38, 39, 41, 44, 45, 47</td>
</tr>
<tr>
<td>Piling/Anchoring</td>
<td>5, 27, 37, 39</td>
</tr>
<tr>
<td>Environmental Applications</td>
<td>24, 27, 29, 30, 32, 33, 37, 39, 42</td>
</tr>
</tbody>
</table>

In fact, the European code of practice for jet grouting supports the need to assure a continuous flow of spoil return to the surface during jetting. It is very important to understand that control of the return spoil ensures pressure control of the in situ erosion environment so that no energy is wasted hydrofracturing the soil in lieu of eroding the soil.

Quality jet grouting is reliant on continuity of erosion parameters and controlling the erosion environment. This is particularly so when the inspection issues are nearly all procedural and repetition is all important. Different soil types exhibit different erodibility characteristics (Fig. 2.4-2).
Cohesionless soils are relatively easy to erode as they have no binder (other than moisture) and are actually self erosive when subject to such a turbulent environment. At the other end of the scale, clays are difficult to erode as they are bound by cohesion. It should be noted here also that up-hole velocities are not generally great enough to exhaust particles larger than a fine sand size. Plastic clays, for example, will generally break in chunks and pieces rather than small particles, and this often causes annulus plugging and spoil return loss. This could be cause for hydrofracturing and poor control of Soilcrete quality and geometry. Spoil return can be assisted by multiple nozzles, air sheathing the jet nozzle(s), multiple directions of the nozzles, drill casing, auxiliary air injected above the monitor, multiple cutting lifts, or combinations of the above.

Only specialist experience is currently available to assess which system, method, and procedures will furnish the Soilcrete that achieves the project goals, and in general, more than one system can usually be utilized.

**CURRENT DESIGN PRACTICE**

Underpinning is the application for which jet grouting has been most used in the U.S. This is probably due to the cost and schedule competitiveness of the system, as well as the safety of jet grouting versus conventional systems. This is particularly so when underpinning is also combined with excavation support and groundwater control. In general, underpinning design focuses on developing a geometry of interconnected Soilcrete which is capable of resisting overturning and sliding (Fig 2.4-3). The Soilcrete geometry is assumed to act as a homogenous mass not unlike a gravity wall. Internal stresses are usually checked at critical locations, and the average desired unconfined compressive strength is typically set at three times the design requirements.
Where groundwater control alone is required, Soilcrete permeability and wall thickness is usually set. Permeability is one of the most difficult parameters to test for in the field, and has resulted in quality concerns on more than one project. Occasionally, modulus is also a criterion, depending on design deformation requirements.

For tunnel stabilization, a strength criterion is all that is usually desired, along with a somewhat homogenous Soilcrete matrix. This is the case in microtunneling and tunnel boring machine work where groundwater intrusion and face stability are serious problems. On at least one occasion in the US, nearly horizontal jet grouting has been applied to create a tunnel roof structure (similar to forepoling). This has proven successful in Europe when applied to the New Austrian Tunneling Method in unsaturated ground.

CONSTRUCTION METHODS AND MATERIALS

In general, all systems of jet grouting have similar basic construction procedures:

1. Set up on location at design angle of penetration
2. Drill to depth by hydraulic rotary methods
3. Commence jet grouting at the base of the design depth, lifting (and rotating if required) uniformly until the design top is reached

Many variations to these procedures have been developed to overcome drilling difficulties or ensure waste return. These include:

Access: Pre-drilling, cased hole drilling, using a Down-the-Hole hammer beneath the monitor, high flow drill fluid injection, high pressure drill fluid injection and drill fluid variations.

Erosion: Precutting, double cutting, multiple nozzles, angled nozzles, auxiliary air nozzles, high pressure air, increased high pressure fluid, ultra-high pressure of fluid injection, and relief hole placement.

The equipment to perform jet grouting remains specialized, but a sufficient number of vendors are available. Drills range from miniature, electrically powered units to large crane supported systems. Some drills have the ability to create a wide variety of Soilcrete geometries through specialized controls for rotation and lift (Fig. 24-4).
Pumping systems are also specialized, and usually range from 300 to 500 Horsepower. Most triple system pumps are containerized so that the three parameters (air, water, grout) are centrally controlled and monitored.

Slurry preparation can be very simple, manual mixing or it can be highly automated. This is so for both batch system mixing or continuous jet mixing operations. In any case, jet grouting requires the ability to batch slurry at a rate of 5 to 25 m3/hr (6 to 32 yd3/hr), depending on the system applied, at specific gravities of 1.4 to 1.8. The sequence of Soilcrete production is an important factor in the production of quality Soilcrete. This is a consideration for all jet grouting projects, but particularly when the application includes underpinning.

The work plan for jet grouting is also important and is somewhat integrated into the sequence of operations. A few things to note here:

* Angle jet grouting beyond 30° from vertical should not use air as a component, as it tends to fracture the ground and cause heave.
* Always consider work to be done in a primary, secondary, tertiary, etc sequence.
* In general, work should progress from low in situ stress regions to high in situ stress regions; that is to say, when underpinning, start beyond the edge of a column footing and progress daily closer to the center until the design coverage is achieved. This will allow soil to "arch" and minimize structure deformations until the Soilcrete cures sufficiently to accept load.

Jet grouting materials typically use blends of water and cement. It has been found that a variety of cement additives are usefully applied to delay set, reduce shrinkage, reduce permeability, ease equipment cleanup, and improve pumpability. Slag cements, fly ash, and swelling clays have also been used successfully. Future environmental applications will include specially developed materials for very low permeability, chemical reactivity in permeable walls, or to increase permeability for selective groundwater control.

**QUALITY CONTROL/QUALITY ASSURANCE**

The basic method of jet grouting construction is procedural; that is to say that one should maintain the jet grouting parameters and materials consistent with the approved test section. The need for installing test elements of Soilcrete and checking for quality and geometry, prior to production work remain a necessity. Unless one has worked at the specific site before, it is not possible to predict jet grouting parameters with precision. It is however, possible to estimate these values from past experience in similar conditions. These parameters include:

- **Drilling**
  - Bit (hole) diameter, drilling slurry makeup
- **Drill Settings**
  - Lift speed, rotation speed, number of lifts
- **Monitor**
  - Nozzle/port sizes for all components injected, angle of the nozzle( s ), number of nozzles
- **Injection**
  - Volume and pressure of all components injected
- **Material**
  - Method of mixing and material components and their concentration(s)

In some cases, grout mixes should be tested in the laboratory to ensure that the quality desired can be achieved. Ordinarily, this can be predicted with reasonable accuracy by knowing the material type and amount of cement injected. Kauschinger (Kausehliger et al 1992) identifies a useful method to evaluate in situ cement content. Additionally, by measuring waste return unit weight one should be able to assess geometry of Soilcrete. However, this geometry prediction method has not proven reliable, and coring/excavation remains the best method to assess geometry.

Over the past ten years, a variety of methods to sample and test Soilcrete have been developed as shown in Table 24-2. Devices have been developed to retrieve wet grab samples at any depth, provided the sampler can be inserted in the uncured Soilcrete to the depth desired. If the ground is very sandy and/or includes cobbles and boulders, this
will restrict deep insertion. Wet grab samples are usually poured into small molds and cured and tested like a concrete cylinder.

Table 2 Sampling and Testing Methods

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Sample Method(s)</th>
<th>Test Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength</td>
<td>Wet grab (in situ) cast in to molds</td>
<td>Unconfined Compression</td>
</tr>
<tr>
<td></td>
<td>Cast in place plastic pipe retrieved</td>
<td>Triaxial</td>
</tr>
<tr>
<td></td>
<td>after cure</td>
<td>Tension</td>
</tr>
<tr>
<td></td>
<td>Core drilling</td>
<td>Direct Shear</td>
</tr>
<tr>
<td>Permeability</td>
<td>As above plus</td>
<td>CPT (in situ) if soft enough</td>
</tr>
<tr>
<td></td>
<td>Cast-in-Place Piezometer</td>
<td>Permeometer</td>
</tr>
<tr>
<td></td>
<td>Drilled and cast</td>
<td>Rising or Falling Head</td>
</tr>
<tr>
<td></td>
<td>Piezometer</td>
<td>(in situ)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Packer Testing</td>
</tr>
</tbody>
</table>

When permeability is a requirement, that test method and its employment should be understood. The only true method to test this is to perform pump testing in a Soilcrete contained soil "tub." It is nondestructive and reliable. Cast-in-place piezometers have shown reasonable accuracy and have correlated well to wet sample results. Packer testing relies on the assumption that Soilcrete can be cored nondestructively. This has proven to be very difficult, and the results from packer tests have shown highly variable correlation to wet grab sample tests or in situ tests.

Fig. 2.4-6. Jet grouting profile.
NEW APPLICATION OF JET GROUTING

As previously shown in Table 24-1, and also discussed under current design practice, the majority of documented jet grouting applications to date have been for either underpinning, excavation support, or groundwater control. More recently, however, jet grouting technology has been used to meet all three of these traditional requirements in a single project, and has also been applied in other, less traditional areas with considerable success, paving the way to even wider acceptance and usage in the future.

Virginia Key Waste Water Treatment Plant, Virginia Key, Florida

Prior to incorporation of a storm surge pressure relief system into an existing outfall pipe, all three project requirements of underpinning in-place utilities, excavation support, and groundwater control were able to be met by jet grouting. Subsurface investigation had determined 58 m (19 ft) of loose to medium dense sand with peat inclusions overlying weathered limestone and limestone bedrock. Groundwater was at 0.91 m (3 ft). As shown in Fig 24-5, triple-rod jet grouting was performed at each end of the excavation area adjacent to and below the 2.6 m (8.5 ft) diameter pipe down to bedrock. Angled drilling and jet grouting beneath the pipe invert completed the encapsulation, thus forming a groundwater seepage barrier as well as excavation support and underpinning across the width of the excavation. Sheet piles connected the sides of the excavation with the grouted zones.
**Nimitz Relief Sewer, Honolulu, Hawaii**

As a value-engineered and less disruptive alternative to open cut construction, jet grouting provided a homogenized tunnel horizon for the installation of a 1.4 m (4.6 ft) relief sewer through soft, lagoonal deposits. Two rows of 1.2 m (4 ft) diameter, interconnected Soilcrete columns were installed over 800 lm (2600 ft) of tunnel alignment to prepare an encapsulated horizon for micro-tunneling. Alternate columns extended to coral formation bedrock at an average depth of 6.7 m (22 ft) below grade, while intermediate columns terminated at 0.91 m (3 ft) below tunnel invert (Fig. 2.4-6). This design provided a fully stabilized tunneling face and mitigated the potential for post-construction settlement.

**Philadelphia International Airport, Philadelphia, Pennsylvania**

Before construction of a portion of the airport's new commuter runway over a former Superfund site, additional site remediation was needed to meet U.S Environmental Protection Agency final closure requirements. The site, previously used to dispose of solid waste incinerator ash and other hazardous materials, was clay capped in the 1980's. In order for Philadelphia's Division of Aviation to use the site, a closure plan was developed, one component of which was the installation of a low permeability horizontal barrier above a very thin natural clay stratum underlaying approximately 1020 m² (11,000 ft²) of the 150,000 m² (37 acre) landfill footprint. The new barrier was constructed using double-rod jet grouting techniques to excavate and replace the bottom 0.91 m (3 ft) of the waste mass with a grout specially formulated to meet the low permeability, low elastic modulus, and compressive strength requirements of the project design. As shown in Fig. 2.4-7, jet grouting ensured the minimum 1.52 m (5 ft) barrier needed to comply with closure specifications.

**NEW DEVELOPMENTS**

Like other ground treatment methods, jet grouting has evolved and, along with the new applications described above, new enhancements continue to be applied. Most of these have come from Europe and Asia, where the system has significantly longer history, but a few have been initiated in the U.S.

1. **Sacrificial Casing**: This is the use of pre-installed sacrificial plastic casing to aid in controlling spoil return and maintain a consistent grouting environment (Viner and Wooden 1990). This thin wall PVC casing is weakly grouted in a predrilled hole, and when Jet grouting commences is blasted into small pieces by the cutting jet.
while acting as a stable borehole to permit ease of return spoils. This is particularly helpful for near-horizontal works, but may be applied in future work for deep applications [>25m (82 ft)]

2. Anchorage Applications: In Europe, the jet grouting system has been employed to effect higher anchor capacities in weak soils (Ground Engineering 1988) Jet grouting for the bond zone creates a large bond area, and provided grout quality is high enough, permits transfer of higher friction capacities from the soil to the anchor

3. Super Jet Grouting: Where soil stabilization of soft soils is necessary, jumbo jet grouting has been effective This is similar to Triple System jet grouting, except that the erosion energy is boosted by increasing the volume of the jetted fluid. This is coincident with a grout rate boost to stabilize these large diameter elements which can reach 5m (164 ft)

4. Cross Jetting: In an effort to better control quality and geometry cross jetting has been developed (Shibazaki, Yoshida and Matsumoto 1996) This technology uses a pair of water/air nozzles aligned to intersect at a specific point At this point, the fluid impact quickly dissipates the energy. With slow, consistent rotation and lift, a controlled geometry is eroded, and thus a design grout injection can be made providing a higher degree of Soilcrete quality and consistency.

5. Directional Drilling combined with Jet Grouting: This variation of single system jet grouting is currently being experimented with in Europe It has application in providing horizontal barriers for groundwater or leachate control

6. Combined Mechanical Mixing and Jet Grouting: Applying jet grouting to mechanical systems provides the addition of hydraulic erosion energy to the mechanical mixing energy (Miyoshi and Hirayama 1996) As a growing ground treatment system in Japan, it is expected to be applied more widely as a ground stabilization system.

CONCLUSIONS
The next ten years of jet grouting are expected to expand on these new developments Additionally, new grout materials will be introduced to enhance Soilcrete quality, and applications for environmental remediation are inevitable Present practice will continue to grow as the engineering community learns more about the variety of applications for jet grouting and its effectiveness.

CHRONOLOGICAL BIBLIOGRAPHY OF READILY AVAILABLE PUBLICATIONS ON U.S. JET GROUTING: 1986 -1996
Refer to Table 2.4-1 for corresponding application


27. Soil Washing IJS Patent No 5,098,224 Process and Device for the Decontamination of Contaminated Sites


Jet Grouting  Jet grouting is the newest of the grouting methods and is rapidly becoming the most widely used. Jet grouting uses high pressure jets to break up the soils and replace them with a mixture of excavated soils and cement, typically referred to as "soilcrete". There are a number of variations of jet grouting depending on the details of the application and on the experience and expertise of both the designer and the contractor.

The design of a jet-grouted column is influenced by a number of interdependent variables related to in situ soil conditions, materials used, and operating parameters. Table 7-11 presents a summary of the principal variables of the jet grouting system and their potential impact on the three basic design aspects of the jet-grouted wall: column diameter, strength and permeability. Table 7-11 gives typical ranges of operating parameters and results achieved by the three basic injection systems of jet grouting. It should be noted however, that the grout pressures indicated in this table are based on certain equipment and can vary. This table can be used in feasibility studies and preliminary design of jet-grouted wall systems. The actual operating parameters used in production are usually determined from initial field trials performed at the beginning of construction.

Jet grouting is frequently used as a ground control measure in conjunction with tunneling in soft ground using Sequential Excavation Method (Chapter 9).

<table>
<thead>
<tr>
<th>Principal Variables</th>
<th>General Effect of the Variable on Basic Design Elements (Strength, Permeability and Column Diameter)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(a) Jet-Grouted Soil Strength</strong></td>
<td></td>
</tr>
<tr>
<td>Degree of mixing of soil and grout</td>
<td>Strength is higher and less variable for higher degree of mixing</td>
</tr>
<tr>
<td>Soil type and gradation</td>
<td>Sands and gravels tend to produce stronger material while clays and silts tend to produce weaker material.</td>
</tr>
<tr>
<td>Cement Factor</td>
<td>Strength increases with an increase in cement factor (weight of cement per volume of jet-grouted mass).</td>
</tr>
<tr>
<td>Water/cement ratio of grouted mass</td>
<td>Strength of the jet-grouted soil mass decreases with increase in in situ water/cement ratio.</td>
</tr>
<tr>
<td>Jet grouting system</td>
<td>The strength of the double fluid system may be reduced due to air entrapment in the soil-grout mix.</td>
</tr>
<tr>
<td>Age of grouted mass</td>
<td>As the jet-grouted soil mass cures, the strength increases but usually at a slower rate than that of concrete.</td>
</tr>
<tr>
<td><strong>(b) Wall Permeability</strong></td>
<td></td>
</tr>
<tr>
<td>Wall continuity</td>
<td>Overall permeability of a jet grout wall is almost entirely contingent on the continuity of the wall between adjacent columns or panels. Plumb, overlapping multiple rows of columns would produce lower overall permeability. In case of obstructions (boulders, utilities, etc.) if complete encapsulations is not achieved</td>
</tr>
</tbody>
</table>
### Table 7-11 Summary of Jet Grouting System Variables and their Impact on Basic Design Elements

<table>
<thead>
<tr>
<th>Principal Variables</th>
<th>General Effect of the Variable on Basic Design Elements (Strength, Permeability and Column Diameter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grout composition</td>
<td>Assuming complete wall continuity and complete replacement of in situ soil, the lowest permeability which can be obtained is that of the grout (typically $10^{-6}$ to $10^{-7}$ cm/sec). Lower permeabilities may be possible if bentonite or similar waterproofing additive is used.</td>
</tr>
<tr>
<td>Soil composition</td>
<td>If complete replacement is obtained (as may be possible with a triple fluid system) then soil composition does not matter. Otherwise, if uniform mixing is achieved then finer grained soils would produce lower permeabilities as compared to granular soils.</td>
</tr>
<tr>
<td>(c) Column Diameter</td>
<td></td>
</tr>
<tr>
<td>Jet grouting system</td>
<td>The diameter of the completed column increases in size as the number of fluids is increased from the single to the triple fluid systems.</td>
</tr>
<tr>
<td>Soil density and gradation</td>
<td>As density increases, column diameter reduces. For granular soils, the diameter increases with reducing uniformity coefficient ($D_{60}/D_{10}$).</td>
</tr>
<tr>
<td>Degree of mixing of soil and grout</td>
<td></td>
</tr>
</tbody>
</table>