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# GROUND CONTROL AND IMPROVEMENT

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# CHAPTER 8

# JET GROUTING

Since jet grouting is still a relatively new technique, technical papers tend largely to be of the case history type, but with introductory sections summarizing the generalities of evolution, methodologies, advantages, applications, and so on. Much of the data are common to most papers and it would be repetitive to cite specific references for all such information. However, there are three particular sources that have proved of basic value, and from which much of the following is derived: Bruce (1988), Kauschinger and Welsh (1989), and Gallavresi (1992). The author acknowledges the permissions by Dr. Gallavresi, Prof. Kauschinger, Mr. Welsh, and their co-workers to recount so much of their writings in the following sections.

## 8-1 HISTORICAL DEVELOPMENT

Previous research and experience with high-pressure water cutting, for example in American coal mines, and conceptual developments in Britain (Nicholson, 1963) were seized upon by Japanese specialists in the mid-1960s. The original developments and studies using these principles to not only cut and erode, but to cement, soils were conducted about 1965 by the Yamakado brothers (Miki and Nikanishi, 1984). By early 1970, two competing forms of jet grouting had been developed (Figures 8-1 and 8-2 and Table 8-1).

The Chemical Churning Pile (CCP) method originally developed by Nakanishi and co-workers (Miki, 1973; Nakanishi, 1974) used chemical grouts as the jetting medium. These were ejected through nozzles 1.2 to 2.0 mm in diameter, located at the bottom of a simple drill rod that was rotated during injection. However, due to environmental concerns, chemical grouts were soon replaced by cement-based

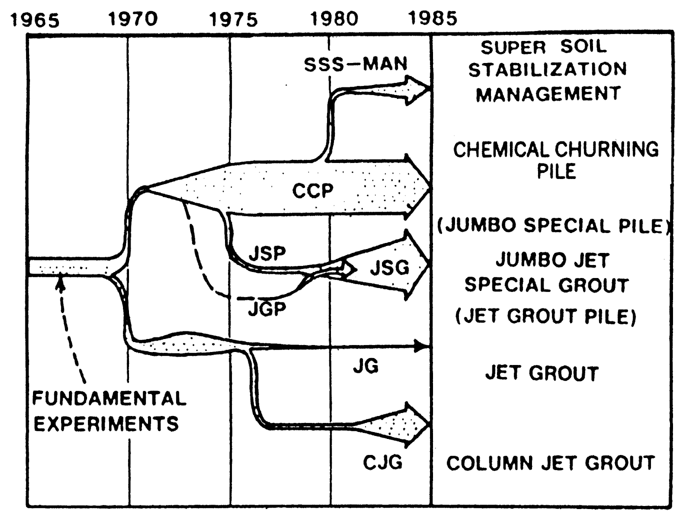


**Figure 8-1** Development of jet grouting methods in Japan. (From Miki and Nakanishi, 1984.)

grouts, although for proprietary reasons the name CCP was preserved. In 1973, an Italian contractor became the first to form CCP columns using "ultra high pressures" (35 MPa) and high flow rates (100 to 250 liters/min), through two slightly larger nozzles (up to 2.4-mm diameter). This system is still widely used, for example, in South America (Guatteri et al., 1988).

By 1972, the CCP group in Japan had also developed the "Jumbo Special Pile" (JSP) method using compressed air as an envelope around the grout jet to give column diameters of 80 to 200 cm. Meanwhile, a "Jet Grout Pile" (JGP) method was being simultaneously developed by another independent group, and JSP and JGP merged around 1980 into the "Jumbo Jet Special Grout" (JSG) method.

The major rival group, headed by Yahiro (Yahiro and Yoshida, 1973, 1974; Yahiro et al., 1975), had also developed in 1970 the "Jet Grout" (JG) method, in which a horizontal high-speed water jet was used monodirectionally to excavate a panel, filled progressively from below with grout. By 1975, however, they had also adopted the idea of rotating the rods during withdrawal, giving birth to the "Column Jet Grout" (CJG) method, which also featured the use of compressed air to focus the upper, water jet.

What Kauschinger and Welsh (1989) refer to as the "last important advance" in jet grouting methodology was pioneered in 1980 by the CCP group in Japan, and first described in 1984 by Miki and Nakanishi. Responding to a request to make a deep, completely watertight wall, they developed the "Super Soil Stabilization Management Method" (SSS-MAN) (Figure 8-3). First, a pilot hole is drilled by reverse circulation, and then a rotating "super high pressure" air-enhanced water jet is lowered to excavate the soil to a greater diameter. The void is then surveyed with

| Method | CCP : Mixing method using a high speed grout jet. ≡ F1 | JSG : Mixing method using a high speed grout jet enveloped by air jet. ≡ F2 | CJG : Half-replacement meyhod using a high speed water jet enveloped by air jet. ≡ F3 | SSS-MAN : Reverse type replacement method using a high speed water jet enveloped by air jet. |
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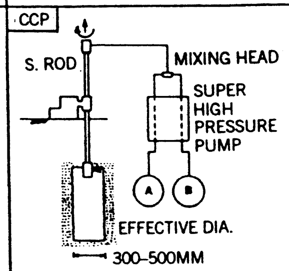
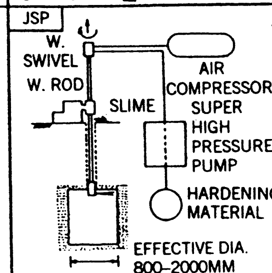
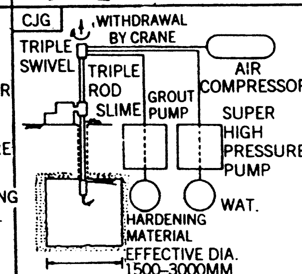
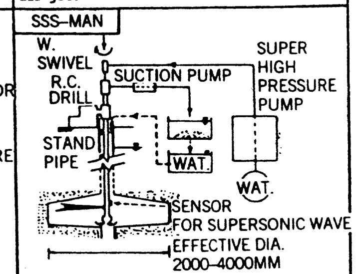
| Schematic Diagram |  |  |  |  |
| Outline of Method | Uplift of a rotating horizontnl griut jet with a super high-pressure (20 MPa) mixes in situ soil with the grout and produces a cylindrically solidified body. | Uplift of a rotating high-speed horizontal grout jet enveloped by air jet mixes in situ soil with the grout and produces a large-size cylindrical solidified body. | Uplift of a rotating high pressure water jet enveloped by air jet cut in situ soil, which is halfly removed by the uplift flow of the air, then a space formed by that removement is mixed with the grout continuously supplied from a rod to produce a large-size cylindrical solidified body. | A pilot hole is drilled by reverse circulation, then a rotating super high pressure (60 MPa) water jet enveloped by air jet is lowered removing the cut soil through the reverse rod to produce a large-size space, which is filled up with grout after the confirmation of the space shape. |
| Fit Soil | cohesive soil , sandy soil ( N<5 ) ( N<15 ) | cohesive soil , sandy soil gravelly soil | cohesive soil , sandy soil | cohesive soil , sandy soil gravelly soil |
| Improvement efficiency | An improved diameter of 300-500 mm and a high strength with uniformity are attainable. | A large size improved diameter of 800-2000 mm and a high strength with uniformity are attainable. | A large -size improved diameter of 1500-3000 mm and a high strength with uniformity are attainable. | A large-size cylindrically solidified body having the diameter of 2000-4000 mm is attainable per one rod. As grout, concrete, clay, cement mortar, etc can be used. The diameter of a body can be confirmed on the ground, so a severe management can be done. |

**Figure 8-2** Illustrations of jet grouting methods used in Japan. (From Miki and Nakanishi, 1984.)

**TABLE 8-1 Major Categories of Jet Grouting Methods**

| Original Japanese Name | Principle of Operation | Jetting Pressure (MPa) | Jetting Nozzle Diameter (mm) | Rotation Rate (rpm) | Anticipated Column Diameter (cm) | Notes |
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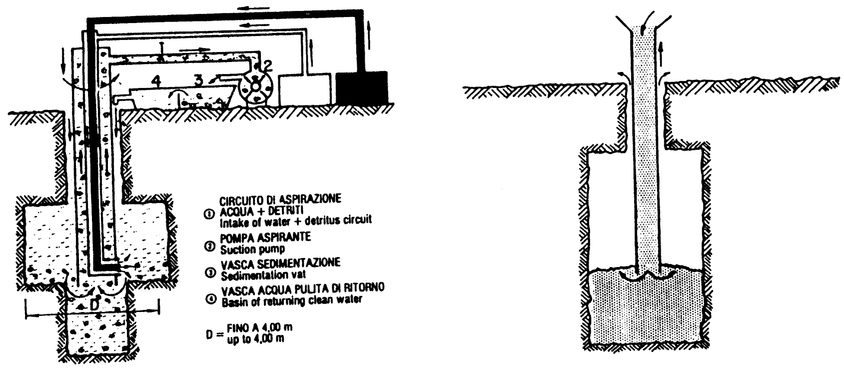
|---|---|---|---|---|---|---|
| Jet Grout (JG) | Upper water and lower grout jet | 20 | ? | None | —— | Panels only, soon obsolete |
| Chemical Churning Pile (CCP) | Single grout jet | 20–40 | 1.2–3.0 | 20 | 30–60 | 1. Chemicals now replaced by cement<br>2. Similar to Rodinjet 1 (Fl) |
| Jumbo Special Grout (JSG) | Single jet of grout enveloped in air | 20 | 3–3.2 | 6 | 80–200 | 1. Originally called "jumbo special pile" (JSP) but name changed for patent reasons<br>2. Similar to Rodinjet 2 (F2) |
| Column Jet Grout (CJG) | Upper water and air jet and lower grout jet | 40–50 | 1.8–3.0 (upper) 3.0–5.0 (lower) (8–9 mm in Kajima system) | 5 | 150–300 | 1. Referred to as "half replacement"<br>2. Similar to Rodinjet 3 or Kajima/GKN Keller system (F3) |
| Mini Max (MM) | Like CCP but uses special "chemicolime" cement | 20 | 1.2 | 20 | 80-–160 | Specially for very weak soil and organics (e.g., soft peaty clays under water) |
| Jumbo Mini Max (JMM) | As for MM except for addition of 20–40 cm wing jet | 20 | 1.2 | 20 | 200 | Specially for very weak soil and organics (e.g., soft peaty clays under water) |
| Super Soil Stabilization Management (SSS-Man) | Air water jet used to excavate volume completely underwater; this is then surveyed ultrasonically; if OK, then tremied full of desired material | 20–60 | 2–2.8 | 3–7 | 200–400 | 1. To provide absolute control over shape and composition of column<br>2. Effective to over 70-m depth<br>3. "Complete replacement"<br>4. Most expensive technique, but ensures desired performance |

*Source:* From Bruce (1988).




| FLUIDI UTILIZZATI Fluid utilized | PRESSIONE Pressure | | |
|---|---|---|---|
| | I° FASE 1st phase | II° FASE 2nd phase | III° FASE 3rd phase |
| ACQUA Water | 20 MPa 200 BAR | 40 MPa 400 BAR | 60 MPa 600 BAR |
| ARIA COMPRESSA Compressed air | | (?) ? | |

**Figure 8-3** Details of SSS-MAN method. (From Trevi, 1990.)

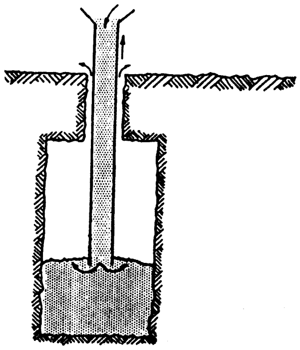
a sonic transducer (MASU—Mitsui Automatic Scanner of Underground) and further jetting conducted if required. The water-filled space is then backfilled by tremie placement of the selected grout or concrete.

By the late 1970s, most of the basic techniques were sought, under license, by groups of geotechnical contractors throughout the world, but initially and primarily in Germany, Italy, France, Singapore, and Brazil. As discussed in Section 8.3., this scope has widened considerably over the last decade to the extent that applications have been recorded throughout the world, on every continent.

In North America, the idea was first promoted in 1979, although by 1984 only a handful of small projects had been completed using either one-fluid or three-fluid systems. The slow acceptance of the method (Andromalos and Pettit, 1986) reflected a number of drawbacks including risk/legal concerns such as are associated with any novel method; inappropriate applications; initial technical problems leading to poor performance; and simply, a lack of commercial demand for the technique. In the last few years, however, a limited number of specialty contractors have conducted numerous, effective works (Burke et al., 1989) but typically and conservatively only for one purpose (structural underpinning) in one soil category (sands and gravels).

Despite all the ongoing developments and refinements, there are basically only three methods that are being used, and these may be generically classified as follows:

- *F1—One-Fluid System:* The fluid is grout, and in this system the jet simultaneously erodes and injects. It involves only partial replacement of the soil.



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*l replacement of the soil.*



- *F2—Two-Fluid System:* This method uses a cement jet inside a compressed air cone. F2 gives a larger column diameter than F1 and gives a higher degree of soil replacement.
- *F3—Three-Fluid System:* Here, an upper ejection of water inside an air envelope is used for excavation, with a lower jet emitting grout for replacement of jetted soil.

These generic classes are now described in detail. Overall, on an international basis, the simplicity and versatility of the F1 method ensure that it is still the most common, although there are considerable national variations depending on the application of the jet grouting.

## 8-2 GENERAL OPERATIONAL FEATURES OF THE THREE GENERIC METHODS

Table 8-2 provides a general summary of operational parameters and grouted soil strengths. However, it must be noted that these data represent a typical range, and the details are dictated on any one project by a number of variables. For the F1 system, six jetting parameters must be determined: grout pressure, number and size of nozzles, w/c ratio, drill rod lifting rate, and rotational speed. For F2, there are two additional variables (air pressure and delivery rate), while for F3 there are ten parameters (the seven for F2 plus water pressure and water jet nozzle size and number).

F1 is the simplest and most straightforward method. The grout jet cuts, removes, and mixes the soil and so provides essentially a mix-in-place effect. In F2 and F3, the air also aids evacuation of the debris, but as the jet is rotated from vertical to horizontal, the air lifting efficiency decreases. Therefore, F1 is used almost exclusively for horizontal jet grouting. As noted by Kauschinger et al. (1992b), field data indicate that there is "significant" compaction of soil outside the perimeter of the jet grout column for a distance of about half a column diameter. As shown in Table 8-2, these column diameters are typically 40 to 60 cm (cohesive soils) and 50 to 120 cm (granulars). *For the same amount of cement injected per volume treated, F1 produces the strongest soilcrete in granular soils. The technical limitations of the* simple fluid system are strongly influenced by the horsepower and flow rate of the grout pump. The drill rods are usually 90 to 110 mm in diameter, and have a 10-mm wall thickness.

With the F2 method, the compressed air enhances the cutting effect of the jet to the extent that columns twice the diameter of F1 columns can be created. This enhancement is due to these factors:

- The air acts as a buffer between the jet stream and any groundwater present, permitting deeper penetration by the jet.
- The soil cut by the jet is prevented from falling back onto the jet, thus reducing *the energy lost through the turbulent action of the cut soil.*

**TABLE 8-2 Typical Range of Jet Grouting Parameters and Soilcrete Formed Using the Single, Double, and Triple Fluid Systems**

| Jetting Parameter | | F1 | F2 | F3 |
|---|---|---|---|---|
| Injection pressure | | | | |
| Water jet | (MPa) | PW[a] | PW | 30–55 |
| Grout jet | (MPa) | 30–55 | 30–55 | 1–4 |
| Compressed air | (MPa) | Not used | 0.7–1.7 | 0.7–1.7 |
| Flow rates | | | | |
| Water jet | (liters/min) | PW | PW | 70–100 |
| Grout jet | (liters/min) | 60–150 | 100–150 | 150–250 |
| Compressed air | ($m^3$/min) | Not used | 1–3 | 1–3 |
| Nozzle sizes | | | | |
| Water jet | (mm) | PW | PW | 1.8–2.6 |
| Grout jet | (mm) | 1.8–3.0 | 2.4–3.4 | 3.5–6 |
| Number of water jets | | PW | PW | 1–2 |
| Number of grout jets | | 2–6 | 1–2 | 1 |
| Cement grout W–C ratio | | | 0.80–1 to 2–1 | |
| Cement consumption | (kg/m) | 200–500 | 300–1000 | 500–2000 |
| | (kg/$m^3$) | 400–1000 | 150–550 | 150–650 |
| Rod rotation speed | (rpm) | 10–30 | 10–30 | 3–8 |
| Lifting speed | (min/m) | 3–8 | 3–10 | 10–25 |
| Column diameter: | | | | |
| Coarse-grained soil | (m) | 0.5–1 | 1–2 | 1.5–3 |
| Fine-grained soil | (m) | 0.4–0.8 | 1–1.5 | 1–2 |
| Soilcrete strength | | | | |
| Sandy soil | (MPa) | 10–30 | 7.5–15 | 10–20 |
| Clayey soil | (MPa) | 1.5–10 | 1.5–5 | 1.5–7.5 |

*Source:* From Kauschinger and Welsh (1989).
[a]PW = Water jets only used during prewashing.

- The cut soil is more efficiently removed from the region of jetting by the bubbling action of the compressed air.

The major drawback with F2 is that the soilcrete has a higher air content, and so has the lowest strength for any of the systems. F2 also requires rather more complex hardware and techniques. For example, the pathway for conducting the air is a 5-mm-wide annulus between the inner rods (carrying the grout) and the outer rod. This must be kept open, or the process will revert to F1. On the other hand, Guatteri et al. (1988) claim that an operational advantage of F2 is that it permits slightly lower grouting pressures (25 to 33 MPa) to be used, and so causes less wear on the grout pumps.

F3 is the most complicated and slowest system, but permits virtually full replacement of the jetted soil, and provides the largest column diameters. There is no standard practice for selecting which passageway in the triple-rod system carries which medium. The only essential is that the air/water jet be located above the grout injection point. Parry-Davies et al. (1992) found by field observation in sandy, bouldery material that the most efficient geometry featured a 180° gap (in plan) between the direction of the upper (air/water) and lower (grout) nozzles, which had a vertical separation of 150 mm. One procedure is to use the central core to convey the grout (Figure 8-4), with the middle annulus carrying the water and the outer the air. Water can be used during drilling to permit self-jetting of the rods, in appropriate ground conditions. Again, a simple check ball is used to change the direction of flow for the grouting phase. An alternative method features the water in the core; this is mechanically the best arrangement since the highest pressure fluid (i.e., the water) is in the smallest diameter container and so generates the smallest hoop stresses. The air travels in the middle annulus, and the grout in the (larger) outer annulus. If the system is to be self-jetting, then special valving is necessary to seal the bottom of the monitor prior to grouting. (A simple check ball is not possible because the central passage does not typically pass uninterrupted to the bit).

Clearly, the diameter of the column formed and the strength of the cemented soil (soilcrete) are not related only to the grouting method. They are also strongly influenced by many other factors including: soil type, density, plasticity, water content, water table location, amount of cement injected, age of soilcrete, and the energy used to form the column, as discussed in later sections.

Most simply, there are two basic steps in the process: the drilling, and the subsequent grouting.

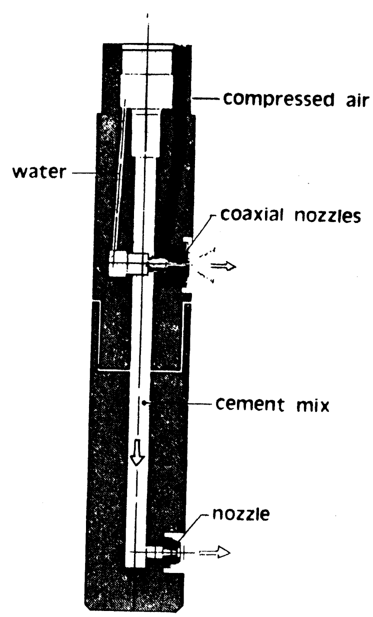


**Figure 8-4** F3 monitor. (From Tornaghi and Perelli Cippo, 1985.)

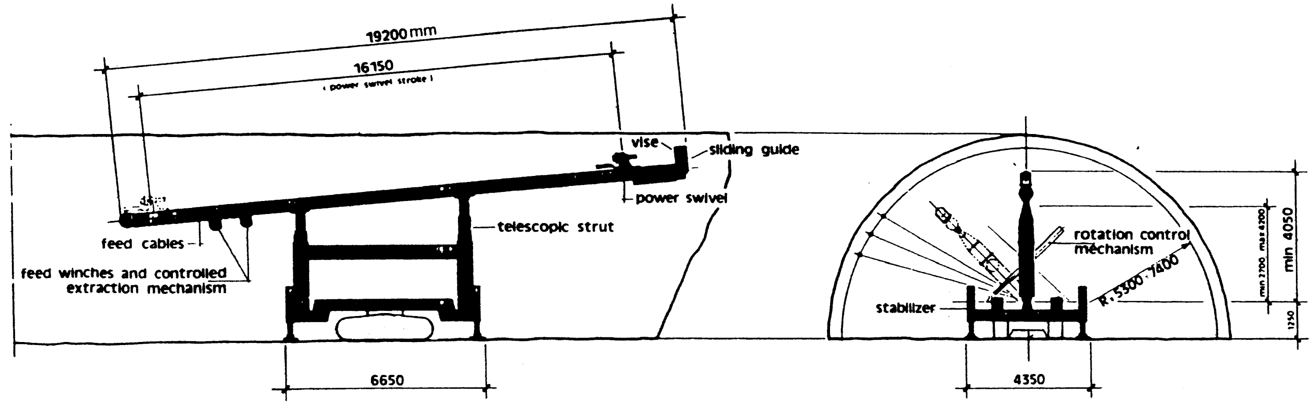


**Figure 8-5** Early model drill rig for subhorizontal jet grouting. (From Tornaghi and Perelli Cippo, 1985.)

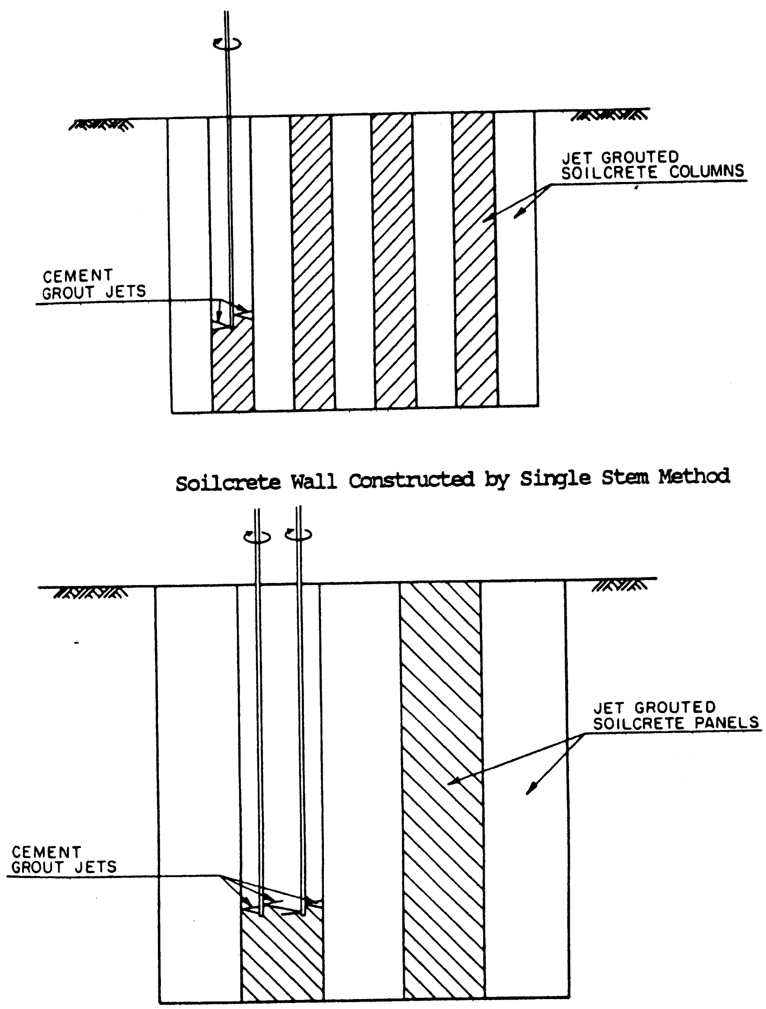


**Figure 8-6** Soilcrete wall constructed by double-stem method, Norfolk, Virginia. (From Andromalos and Gazaway, 1989. Reproduced by permission of ASCE.)

The mode of drilling is selected according to soil conditions, general site features, and the design specifications in regard to hole length and inclination. Rotary drilling is preferred in medium- to fine-grained soils, and relatively small rigs can be used. Temporary drill casing may be needed, but more frequently uncased holes are drilled with direct circulation of water or bentonite slurry. If casing is used, it must obviously be withdrawn after the jetting rod is placed and grouting begins. The use of a rotary head with a hollow spindle running on a mast 4 to 5 m long permits

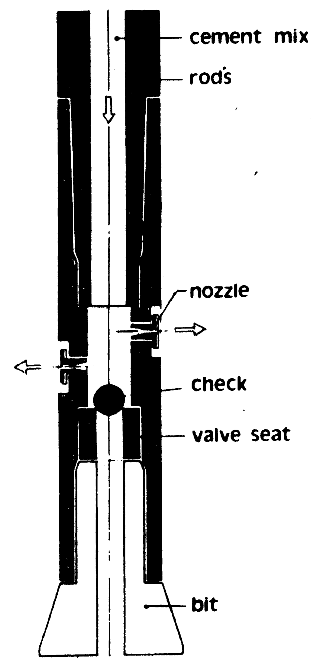


**Figure 8-7** F1 monitor with check ball. (From Tornaghi and Perelli Cippo, 1985.)

the use of a single length of rod to depths of about 16 m. In coarse-grained soils, or those containing cobbles and boulders, rotary percussion may be more suitable, but this requires a heavier rig with a mast as long as the longest rod that is to be used. The use of predrilled guide holes (such as are often necessary with F3 work), nominally 150 mm in diameter, facilitates the spoil discharge, assists in maintaining verticality, and permits a visual check on the continuity of adjacent grouted areas. In theory, the maximum depth of treatment is unlimited (within the scope of geotechnical engineering applications), but the 70 m recorded when stabilizing slide debris in a railroad tunnel near Sempione in Italy is probably a practical maximum (Kauschinger and Welsh, 1989). Figure 8-5 shows the first generation of drill rig that was specially designed for subhorizontal percussive drilling for tunnel work. A system of hydraulic jacks allows the mast to be rotated axially over 180°, and inclined at up to 14° to the horizontal. Using such machines, all the holes necessary for the treatment of a tunnel section ahead of the excavation face can be drilled to a length of 16 m, with a single rod and with no interim setups of the rig. Later rigs are equipped with a movable subplatform permitting a more direct access of the operator to the heading and a greater versatility with respect to the treatment geometry.

Andromalos and Gazaway (1989) describe an interesting development in which the F1 process was conducted by twin 24-m rods (Figure 8-6) suspended on a crane equipped with a set of tubular leads.

The selection of a single rod or very long units (say 25 m) is advantageous not only to maximize productivity but, more importantly, to minimize interruptions (and hence the potential for blockages of nozzles and annuli) during injection. When using the F1 method, the same string of rods (typically 90 mm in diameter), is used for both drilling and grouting, whereas in F3, two strings are usually used consecutively given the delicacy and complexity of the injection string and monitor.

In F1 and F2 a check ball is introduced into the rod after drilling (Figure 8-7) to change the grout jet direction from axial to radial. Water jetting through the bottom of the rods during drilling improves the drilling rate and enhances verticality. Some systems also allow for horizontal water jetting during drilling.

Jet grouting uses heavy duty triplex piston pumps, of around 400 HP, often adapted from high-pressure oil field duties, to pump water or cement grouts. They typically have maximum pressure capacities of well over 70 MPa, although they operate considerably below this ceiling in jet grouting applications.

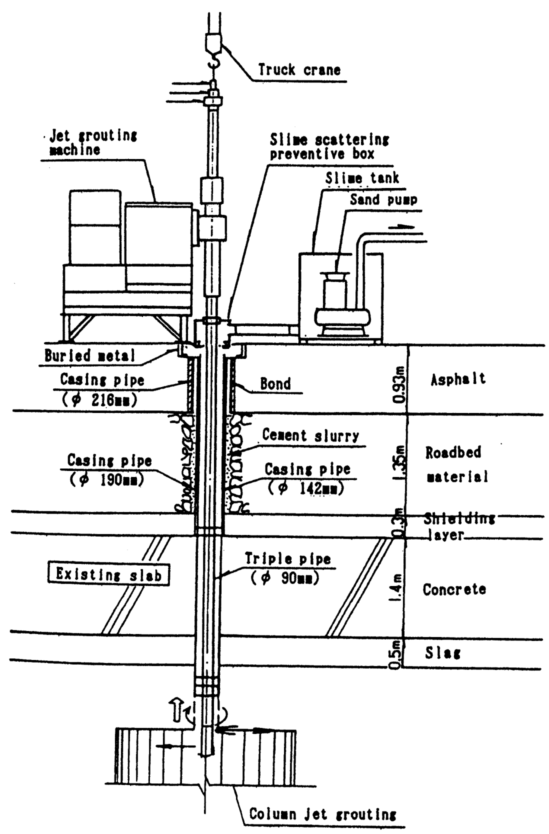


**Figure 8-8** Guide pipe and recovery of effluent, Japan. (From Ichihashi et al., 1992. Reproduced by permission of ASCE.)

Grouts are prepared in automatic batch plants, specially designed to provide accurate proportioning and efficient colloidal mixing at rates adequate to meet the site demands: each drill rig may require up to 8 $m^3$ of grout per hour when jetting, and supply to the rig must not be interrupted during this operation.

During jetting, it is essential that the displaced slurry (and excess grout) can reach the surface with minimum impedence. If an annular pathway is not maintained, uncontrolled and usually unwanted ground heave or lateral movements will result. In the case of soft clays, heaves of up to 1 m have been reported (Kauschinger and Welsh, 1989). It may be necessary to design special procedures for preventing this, as well as for the handling and disposal of the spoil—especially important in urban areas and/or where the spoil may be contaminated or hazardous. Figure 8-8 is a good example of a system used during treatment of soils under an airport in Japan (Ichihashi et al., 1992). Burke et al. (1989) claim that F3 is the least likely to cause heave since "the water/soil/air mixture is of lower density and easily flows up the drill annulus as waste."

## 8-3 APPLICATIONS

One of the primary advantages of the jet grouting principle over other types of grouting is that it can be used across the whole spectrum of soils from the coarsest gravels to the finest clays. In addition, since the soil is partially or completely removed, its virgin permeability does not dictate grout acceptance and so costs can be more closely predicted (Coomber, 1985a). Since large diameter columns can be created from relatively small boreholes, local obstructions such as timber piles or large boulders can be bypassed or incorporated into the soilcrete. Jet grouting can be conducted from any suitable access point, and can be terminated at any elevation, providing treatment only in the target zones. It can be conducted vertically or (sub)horizontally, above or below the water table.

Potential disadvantages include the possibility of heave or lateral movements, and difficulties of spoil handling and removal. (In this regard, however, the grout/soil mix expelled typically hardens within 24 hr and can then be disposed of as solid residue.) Other disadvantages lie in the general lack of an economic means for measuring the dimensions of a large number of columns in a routine production project. In addition, soilcrete strengths tend to be much more variable than concrete, being strongly influenced by the silt and clay content of the native soil (Section 8-4). Also, if the groundwater flow velocities are high, the fluid soilcrete may experience local removal of the cement prior to its stiffening, and so unevenness in quality.

As for any other ground engineering construction option, the viability of jet grouting typically requires a positive conclusion from two independent studies: technical and economic. Furthermore, and specifically in the case of a newer technology such as this, there are many cases where jet grouting has been conducted simply to establish a "job reference" for both the contractor and the technique. Based on U.S. experience, this strategically driven motive has occasionally had the

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