JET GROUTING UNDERPINNING OF A BUILDING IN THE US

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This job was done in Morristown, NJ, with mono fluid system jet grouting for the construction of a new bank building. After the demolition of the existing two story structures, an excavation in loose sandy fill materials was necessary in order to reach the new structure basement level. Due to this jet grouting was selected as a medium to provide both excavation support and permanent underpinning, minimizing the adjacent building settlements. These two adjacent buildings were partially underpinned with a “gravity wall” made with 2 and 3 rows of secant vertical and inclined jet grout columns.

Besides the classical jet grouting control methods, during the jet grouting execution, all the drilling and grouting parameters were recorded by a proprietary system called “Slogger”. Additionally, after the jet grouting execution, an innovative result control technique was used by means of the application of the same parameter recording system. Some of the production columns were re-drilled and a comparison was made between the obtained drilling parameters and those obtained for the same age test columns.

Under the referred existing conditions and in comparison with the conventional underpinning techniques, this project demonstrated that jet grouting, with proper execution and result control, can be faster than them and can maintain the building structural stability and act, at the same time, as a retention system minimizing the existing building settlements.

EXISTING CONDITIONS

A new branch of the First Morris Bank and Trust Company was constructed in Morristown, NJ during the year 2000. The new building is located at 24 North Park Place at the intersection of this street and Washington Street (Figure 1).

This building is a three-story structure with a full basement covering a footprint area of approximately 2,000 square feet. Estimated maximum column loads for this structure are on the order of 136 t.

For the construction of the described building, after the demolition of the existing two story structures that contained full basement, an excavation was necessary in order to reach the new structure basement level, which would be located 1.05 to 2.30 m below the existing basement slab level and 0.90 to 2.15 m below the foundations of the existing 3 story adjacent buildings (Figure 2). This excavation had to be done in loose fill materials composed by fine to coarse sand containing variable but usually small amounts of gravel and silt. This layer had a variable thickness of 1.85 to 3.65 m from the bottom of the existing basement slab to the top of the fractured and weathered schist bedrock.

Due to the referred existing conditions and in comparison with the conventional techniques (pit underpinning and soldier piles and lagging), jet grouting was selected as a similar cost alternative that would be faster than them and would provide both excavation support and permanent underpinning, minimizing the adjacent building settlements.
UNDERPINNING DESIGN

Jet Grouting is the partial replacement and/or mixing of the ground, in-situ, with cement, forming a hard, blended matrix of cement and soil plus rock fragments and debris in some cases. The blending of the cement with the local material is accomplished by injecting water cement grout into the local matrix at very high speed (“jet”), while rotating the “monitor” with the lateral small nozzle(s), located at the end of the drill string, but just above the bit. The high velocity of the grout is created by high pumping pressure forcing it through the referred small nozzle(s). The rotation during injection produces a radius of treated soil. If the injection nozzle is advanced to a projected depth with a drill, then rotated and retracted back up to that depth minus the projected length of the treatment, a radial zone of soil between those depths will be mixed or replaced with cement. The diameter and strength of the zone of influence, known as jet grouting column or element, is dependent on soil type, injection pressure, retraction rate, grout flow rate, grout composition and other factors.

There are basically three jet grouting systems that are generically classified as follows (Figure 3):

- Mono fluid system (F1): One or two jets of grout simultaneously erode and inject the soil producing it partial replacement.
- Double fluid system (F2): One or two jets of grout inside a compressed air cone erode and inject the soil. F2 produces a larger column diameter than F1 and gives a higher degree of soil replacement.
- Triple fluid system (F3): An upper jet of water inside an air cone is used for cutting, with a lower jet of grout for replacement of the pre-cut soil. F3 is the most complicated and slowest system, but permits virtually full replacement of the jetted soil, and provides the largest column diameter.

In this particular case, the two adjacent building foundations were partially underpinned with a "gravity wall" made with 2 and 3 rows of staggered secant vertical and inclined mono fluid system jet grouting columns. This wall maintained the structural stability and acted, at the same time, as a retention system during the new building basement excavation (Figures 4 and 5). A total of 138 columns were laid out to provide adequate support considering the various footing configurations.

Since the mono fluid system produces the smallest column diameter, in this particular application it was selected among the three jet grouting systems to avoid the execution of big temporary soft points under the footings to be underpinned. It also has the additional benefit of creating a relatively low amount of spoils (a maximum of 20 to 30% of the total volume of grout injected) and subsurface disturbance.

The underpinning design was focused on developing a geometry of interconnected jet grouting columns which was capable of resisting overturning and sliding with a safety factor over 1.5. This soil-cement geometry was assumed to act as a homogenous mass not unlike a gravity wall. Internal stresses were checked at critical locations using an average unconfined compressive strength (UCS) with a safety factor of three. The basic assumptions for this design were:

- Soil type: loose to medium dense, fine to medium sands
- Depth to bedrock exceeds bottom of jet grouting
- No groundwater would be encountered
- Jet grouting column diameter: 0.75 m
- Jet grouting column length: 1.8 to 3.6 m
- Distance between column centers: 0.6 m
- Excavation depths: 1.2 to 2.4 m
- Jet grouting UCS: 3.5 MPa
- Jet grouting tensile strength: 7.5% UCS = 2.6 MPa

Using the empirical relationships given by Armijo (1993), Langbehn (1986) and Miki and Nakanishi (1984), the column diameter and UCS were estimated in terms of the following parameters:

- soil type and density (SPT blow count under 10)
- jet grouting system (F1)
- injection pressure (350 to 500 bars)
- amount of cement to be injected per meter of column (300 to 400 kg)

The structural loads considered in this analysis were:

- New building wall: 7.5 t/m
- Adjacent building wall: 5 t/m

Besides the sliding and overturning, the bearing capacity and the location of the resultant force were also checked at the base of the created gravity wall assuming an equivalent footing width. Additionally, compressive and tensile internal stresses were checked at the “legs” of the wall (jet grouting columns). In both cases the assumed design stresses were more than enough. Nevertheless, the columns were reinforced with a # 8 grade 60 (fyk = 420 MPa) steel bar following the standard practice in this kind of jobs and in order to assure a proper connection with the existing footings.

The settlements were considered negligible assuming that the jet grouting columns would be socketed in the bedrock and their deformation modulus is normally around 500 times the UCS.

The jet grout underpinning was incorporated in the structural design as a part of the basement wall, which was completed with a 0.20 m reinforced concrete facing. For this purpose a top jet grouting wedge had to be shaved during the excavation process (Figure 5).

**JET GROUTING EXECUTION**

For this project, a soil-cement matrix was installed as shown on the plans by equipment positioned at the level of the existing adjacent foundations (Figure 6). This matrix was installed from the bottom up with the process of jet grouting, utilizing the single fluid system. It was constructed in situ by advancing the jet grout monitor with a tricone bit to the target depth. During retraction the two 2.2 mm diameter nozzles injected high pressure (in the drilling pipe, before the nozzles) / high speed (in the ground, after the nozzles) cement grout (1 to 1 water : cement by weight) to ‘cut’ the soil and simultaneously mix / replace it with the cement to create the mentioned soil-cement matrix. As the injection process was initiated, the monitor was retracted and rotated at a rate determined by feedback from the “real-time” monitoring of the parameters of the process. Intimate contact was established between jet grouting column and footing by maintaining a positive head of grout above the footing to prevent shrinkage during hardening. Once the target upper elevation was reached, the injection of cement under high pressure was stopped. The monitor was then retracted, drill rig located to the next injection point and the process was repeated.

The final jet grout element spacing was approximately 2.0 feet on center, as discussed before. The injection locations were split-spaced, allowing for the cement treated soil to harden for a minimum of 24 hours, to avoid being disturbed by the next jet grouted element. Jet grouting sequence was such that a minimum distance of two grout element spacing (minimum 2 m) was maintained between jet grout elements in any given day (Table 1). An execution record was provided on all jet grouting columns.

After the drill hole of each column was completed to the required depth, the jet grouting injection commenced according to the parameters established during the previous test program (Column Confirmation Testing, CCT, discussed below). The jet grouting rate of cement injection (pressure and flow), monitor rotation, and rate of monitor withdrawal were programmed into the equipment control system. This was a necessary step in order to reproduce jet grout elements meeting the established requirements of depth, diameter, homogeneity, overlap, and grout quality.

A special proprietary computer program was used to calculate the required time (and consequently the required rate of withdrawal of the monitor) for the grouting process. Utilizing this program, this required time was determined based on the following jet-grouting main parameters (Figure 7):

- Water / cement ratio by weight: 1:1
- Weight of cement per meter of column: 325 kg/m
- Pressure of grout injection: 400 kg/cm²
- Number and diameter of nozzles: 2 with 2.2 mm diameter
This program, which is an application of the Bernoulli’s Equation, and the selected principal parameters, based on previous experience (Table 1), were used to calculate the jet grouting withdrawal time for the test columns. After the CCT was completed and using the data obtained, the same proprietary computer program was applied to the jet grouting production work.

### Quality Assurance / Quality Control

#### Column Confirmation Testing (CCT)

The Column Confirmation Testing (CCT) was employed to sample the treated soil in order to verify conformance with design requirements and evaluate the need to make adjustments to the execution procedures.

CCT was performed on elements installed using production jet grouting equipment and procedures prior to start of production jet grouting. The program included:

1. Installation of a two jet grouted columns at two selected locations.
2. Excavated of the top of these elements to make a visual examination of them for diameter and shape (Figure 8).
3. Coring of the test columns to take 6 samples per element for unconfined compressive strength tests at 3, 7 and 28 days in accordance with ASTM D2938-86 (Figures 9 and 10).

Coring was conducted at least 6 inches radially outward from the axis of the jet grout column center. Cores were marked for 0.30 m of depth. Sufficient samples of the treated soil core were wrapped to preserve moisture until the inspection, selection and testing process.

After this, production columns started to be installed based on the following:

- Results of the 3-days tests. From these results an extrapolation of 28-days test results were made based on plots of unconfined compressive strength with time obtained in previous similar jobs (Andromalos and Gazaway, 1989) or similar laws normally used for concrete.
- Analysis of the drilling and grouting parameters recorded using a proprietary recording system (“SLOGGER”) attached to the equipment (See monitoring section below).
Grout quality
The density of the grout is a direct measurement of the water/cement ratio of the grout mix. Therefore, to monitor its quality, the density of the grout was checked at the turbo mixer using a special density meter or “mud balance”. For a 1:1 water to cement ratio by weight, the density of the grout is 1.51 t/m³ assuming that the density of the cement is equal to 3.05 t/m³.

The density of the spoils was also determined using the same device. The average measured values were 1.62 t/m³. Based on this, the amount of soil mixed with grout in the spoils and consequently the degree of substitution occurred in the soil was estimated around 20%, according to the initial assumptions.

Records and Reports
Daily and final reports were made in accordance with the Project Specifications. Data recorded included:

- Grout hole geometry
- Time and date of beginning and completion of each column
- Injection pressure
- Grout takes (number of batches in the mixer)
- Rates of rotation and withdrawal
- Soil characteristics and spoil amount and density

All data from the jet grouting performance records were compiled and processed to obtain a series of average logs of the hardness (low, medium, high) of the soil and of the amount of spoils (none, medium, total) in terms of the depth (1 graph per 5 production columns). These element types were established so that the distribution was clearly described with respect to chronology and depth.

Additionally, the jet grouting principal parameters were recorded using a proprietary recording system attached to the drilling and jet grouting equipment as described below. These results were presented as the daily drilling and grouting logs.

Monitoring
Recording System
A proprietary recording system, called “SLOGGER”, was used to monitor and record both drilling and grouting parameters. The equipment control panel is shown in Figure 11. During production drilling into the soil, the following parameters were recorded and displayed in real-time:

- Drill Speed
- Rotational Speed
- Torque Pressure
- Drill Feed Pressure
- Depth

Jet grouting equipment was fitted with controls to permit accurate and continuous adjustments to jet grouting related parameters (Figure 12). In addition, such equipment was fitted with an automatic grouting parameter recording system, capable of displaying, in real time, all grouting parameters, and subsequently providing a hard copy for purposes of verification and measurement. The parameters recorded included:

- Depth of Treatment
- Speed of Withdrawal
- Rotational Speed
- Grout Pressure
- Grout Flow Rate

Logs of these drilling and grouting parameters are shown in Figures 13 and 14.
Analysis of Drilling and Grouting Parameters

The real-time monitoring of these parameters is very important. If some mechanical malfunction occurs (such as a drop in pressure or flow rate, or clogging of the nozzles), the rig operator can immediately detect it on the display, and take the necessary actions. In addition, the operator will also inform the engineers of such circumstances and if any change in the subsurface conditions are indicated. Based on this information, the operator can modify the jet grouting process as required.

In this particular job, through the data logging system, the execution of the work was monitored, confirming that it has been carried out correctly and within the design limits. In addition, the recording system permitted the use of the data stored magnetically for the preparation of graphical outputs showing the variation of the measured quantities with depth (Figures 13 and 14)

Structure Movement Monitoring

During the execution of the jet grouting, the foundation being underpinned were monitored for movement (caused by settlement or heave). A general and a local controls were carried out:

General:
Prior to commencing jet grouting, a surveyor established reference points on the structure. Relative elevation measurements were made using fixed benchmarks not affected by the treatment. A minimum of 6 points outside and 6 inside were established. Two full rounds baseline measurements were made.

The reference points were placed both on vertical and horizontal surface, outside and inside the adjacent buildings. The points consisted of drilled-in anchors. Readings were made once a day when active jet grouting was underway.

![Figure 13. Drilling parameter logs](image1)

![Figure 14. Grouting parameter logs](image2)

Local:
It was executed during every jet grouting column installation (See Figure 6) and over the column surrounding area to detect local movements and immediately stop the process if necessary.

The target limiting level of movement was established by the Owner/Structural Engineer in 3 mm, before the commencement of the work. This limit was only reached and passed a little bit during the execution of some of the inclined columns. Due to this, some small fissures appeared in the adjacent buildings, the job was temporarily stopped and a contingency plan was applied. As a result of this plan the column inclination was limited to a maximum of 30° in relationship to the vertical direction and a pretreatment was carried out. By means of this pretreatment, in some selected locations, a relatively low pressure injection was executed in the upper part of the holes with two main purposes:

- Fill the existing voids between the adjacent building foundation and the ground.
- Stabilize the walls of the holes to be re-drilled at the same location for the jet grouting column execution avoiding any obstruction and
allowing the free flow of the spoils through the annular space between the hole walls and the drill rods.

The results of this pretreatment were a complete success and the movements were stopped. After this, the job finished with movements below the fixed target.

** Spoil control**

As previously mentioned, the jet grouting operations produced spoils (a mixture of grout and soil) with a density of about 1.62 t/m³ and a total volume around 20% of the total volume of injected grout. These spoils were continuously monitored and controlled.

A free spoil flowing path was maintained using drill bits sized larger than the drill string and monitor to keep an open annulus between them, and preteating some of the holes and limiting their inclination to 30° as referred in the previous section.

**RESULT CONTROL**

All the measured test column diameters were well over 0.75 m. The UCS obtained from the cores recovered from the same columns were between 7 and 13 Mpa at 28 days with UCS values over 5 Mpa at 3 to 5 days. Due to this, the test column were approved because they exceeded the design assumptions and their jet grouting parameters were adopted for the production work and their drilling and grouting parameter logs were used as a benchmark for comparison purposes during the execution.

These columns were also redrilled with the drilling machine with the recording system attached and the recorded drilling parameters were used to make a comparison with the obtained UCS values and column geometric characteristics. As a result of this comparison it was concluded that the drilling speed through soil cement with UCS > 5 MPa, for the same drill bit, rotational speed, drill pressure and torque, should be under 100 cm/minute. Six production column, at selected locations, where some small incidents were found in the drilling and/or grouting logs, were redrilled along their full length (Figure 15). In all the cases the drilling speed remained under 50 to 100 cm/minute (Figure 16). Due to this, additional coring was not necessary with considerable money and time savings.

The job was completed in 4 weeks and following completion of the work, excavation to full depth additionally confirmed that the jet grouting solution had met the project requirements about jet grout column continuity, diameter and minimum overlap.
CONCLUSIONS

- Under the referred existing conditions and in comparison with the conventional techniques (pit underpinning and soldier piles and lagging), this two projects demonstrated that jet grouting, with proper execution and result control, can be a similar cost alternative. Furthermore, it can be faster than the above mentioned conventional techniques and can maintain the building structural stability and act, at the same time, as a retention system minimizing the existing building settlements.

- The proper execution and result control should include the continuous recording, in real time, of the grouting and drilling parameters using a recording system like the one utilized during this job execution.

- Taking advantage of the same recording system an innovative technique was successfully applied as a result control in this project. Some of the production columns were re-drilled and a comparison was made between the obtained drilling parameters and those obtained for the same age test columns. Drilling speeds under 100 cm/minute were correlated with UCS > 5 Mpa.

- In order to avoid damages to the adjacent structures due to ground heave, the hole inclination should limited to 30º and a pretreatment should be done in areas with inclined holes and where the presence of voids under the existing footings is suspected.

REFERENCES

