An Innovative Approach for Jet Grouting in Soft Clays

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ABSTRACT

The expansion of Keswick Water Pollution Control Plant in 2013 included construction of a new effluent outfall into Lake Simcoe. A major section of the outfall sewer was constructed using a microtunnel boring machine. Jet grouting was specified in order to pre-treat the very soft clay below an existing 750 mm sanitary sewer prior to the new outfall sewer tunnel’s being constructed beneath it. The jet grouting specification stipulated that no movement of the existing sanitary sewer, resulting from jet grouting operations, was allowed.

The double fluid jet grouting process was employed. A pre-production test program was successfully performed to verify jet grouting parameters such as lift rate, rotation rate and injection pressure specific to the soils at this site. During production jet grouting, movement of the sewer was detected, necessitating a temporary stoppage of the work. Without modification to the previously tested jet grouting parameters, an innovative methodology was successfully implemented to eliminate further grouting-induced movement of the sewer. This paper outlines subsurface conditions, results of both the initial and supplemental jet grout test programs, and details pertaining to the innovative methodology employed.

INTRODUCTION

The community of Keswick, Ontario is located on the east shore of Cook Bay at the southern tip of Lake Simcoe. The Keswick Water Pollution Control Plant was expanded in 2013 to accommodate ongoing significant population growth in the area. Part of the plant expansion included construction, by microtunneling, of a new 1200 mm diameter effluent outfall sewer.

Contractor-designed jet grouting of overlapping soil-cement columns was successfully completed to support an existing 750 mm diameter sewer pipe which crosses the new outfall alignment. Jet grouting was required in order to strengthen the ground below the existing sewer to prevent excessive settlement during tunneling at the proposed sewer crossing.

The double fluid jet grouting process was used for installation of the soil-cement columns. A test program was undertaken in representative soils in close proximity to the work area. Jet grouting performance was evaluated via exhumation, probing and sampling of the test columns, and no grouting-induced movement concerns were detected. Based on the test program results, production jet grouting commenced using the same parameters employed in constructing the test columns.

During production work, movement of the sub-surface monitoring points located along the axis of the sewer was detected and jet grouting was stopped. A comprehensive review of data obtained to that point was conducted and an innovative installation methodology was proposed by the contractor for the installation of the jet grout columns to prevent further movement of the sewer.

SUBSURFACE CONDITIONS

In the area of the sewer crossing, silty clay and clayey silt materials are present with SPT 'N' values between 0 and 8, extending from the underside of roadbed down to competent till soil at 13 metres below surface (Fig. 1). The consistency of the native soils vary from a soft to stiff, but are generally soft. In situ vane tests were carried out during geotechnical investigations in 2011, resulting in
shear strengths from 10 to 50 kPa, but generally less than 40 kPa with sensitivities from 1.0 to 5.7.

3 JET GROUTING - OVERVIEW

Jet grouting is a ground modification system used for in situ mixing of soils with a stabilizer (usually neat cement grout). Jet grouting is one of the most versatile ground improvement techniques, and can be applied to cut-off groundwater (Gurpersaud, et al., 2013) and provide structural rigidity, all within a single application (Klaus & Bell, 2013). The stabilizer (grout) is injected at high pressures (typically 300 – 400 bars) through one or more nozzles positioned at the bottom of a small diameter (typically ≤ 89 mm) drill string. Grout is ejected through the nozzles at high velocity, enabling the jet grouting process to hydraulically destroy the natural matrix of the soil, resulting in mixing of the stabilizer with the in situ soils. The constructed product is a homogenous and continuous structural soil-cement element with predictable physical characteristics. Jet grouting can be applied to a wide range of soils from non-cohesive, poorly graded granular soils to cohesive plastic clays. In the most typical case – jet grouting under full rotation of drill rods – a large diameter (1 to 2 m) soil-cement element is constructed.
using a small diameter (102 mm) penetration. A unique aspect of jet grouting is its ability to target discrete horizons while leaving untargeted layers otherwise untouched beyond the 102 mm diameter penetration. Unlike other grouting systems which are based on forced injection into a medium, jet grouting is an erosion-based process, and subsequently can be effective across the widest soil spectrum (Burke & Sehn, 2003).

Jet grouting is highly varied in tooling, procedures, fluids used for erosion and mixing, and the energy applied for jetting these fluids. As a result of the many variables, the technology cannot be simplified and each practitioner draws upon his own experience base (Burke, 2012). The work completed at Keswick WPCP was designed and constructed by specialty geotechnical contractor Geo-Foundations, employing the double fluid jet grouting process.

Double fluid jet grouting is typically constructed from the bottom upwards. During initial advance of the drill string to target depth, no grouting takes place – water or weak grout is circulated as the drilling fluid under pressure just great enough to maintain circulation. Once at depth, grout slurry and compressed air are delivered to the tip of the drill string via separate, concentric passages within the drill string. Grout slurry is ejected laterally through specially designed nozzles that focus the grout stream for maximum erosive effect. The compressed air meets the grout slurry on the downstream side of the nozzle, shrouding the grout slurry jet (Fig. 2) to further amplify its erosive effect. The presence of remnant compressed air within the dynamically energetic column mass also aids in evacuating excess spoil up and out of the hole via the annular space between the outside of the drill rod and the inside of the initial penetration bore wall. Under 360 degree rotation of the drill string, this process results in construction of a large diameter soil-cement column. Column size is dependent on parameters such as rotation rate, lift rate, injection pressure and grout flow rate.

4 SPECIFIED REQUIREMENTS

The jet grouting contractor was responsible for furnishing all design, labour, materials and equipment necessary for the installation of soil-cement elements by jet grouting to increase the compressive and shear strength properties of subsurface soils as required to enable tunneling to take place without resulting in movement of the existing sewer. The following mandatory aspects and performance criteria were specified:

- Prior to production jet grouting, a test program consisting of the construction of a minimum of three overlapping jet grout test columns was required in order to demonstrate that proposed jet grouting method and equipment will produce acceptable results.
- Movement of utilities, in particular the existing 750 mm sanitary sewer which crosses the outfall alignment, will not be tolerated.
- Ground surface heave will not be tolerated.
- The treated soils shall obtain minimum compressive strength of 1 MPa, as evaluated in accordance with ASTM D2938.
- All soil-cement elements must bear on or within dense or stiff/firm soils.
- The contractor shall design the jet grouting program so as to stabilize subsurface soils by either double or triple fluid jet grouting methods (or greater) to provide soil-cement structures of the minimum dimensions shown on contract drawings and meeting specified performance requirements.
- Design of patterns of soil-cement elements to meet defined requirements is the responsibility of the contractor.

5 INITIAL APPROACH TO JET GROUTING

5.1 Initial Methodology

The contractor’s design consisted of 2 parallel grid lines of overlapping 1.2 m diameter columns (Fig.3), one grid line on either side of the existing sewer pipe, slightly battered as required to deliver a constructed soil-cement geometry that would respect the proximity of the existing sewer while still eroding the soil mass directly beneath the sewer, and extending vertically, as deep as required, to bear on till. The double fluid jet grouting process was proposed for the installation of the soil-cement columns, subject to the successful confirmation – via installation and post-construction evaluation – of sacrificial test columns.
Prior to commencing installation of production jet grout columns, the location of the existing 750 mm diameter sewer within the work area was verified, and all buried services within the influence of the jet grouting block were located and marked. Three monitoring points were installed along the axis of the sewer and within the extents of the proposed jet grout installations to enable monitoring on a continuous basis during jet grouting operations. A test program consisting of installation and evaluation of 3 overlapping jet grouted columns was conducted in the vicinity of the production jet grouting location.

A Casagrande C8 drill rig and associated equipment were used to drill and construct the jet grout columns. Water was used as the drilling fluid during initial penetration to target depth (during which no jetting took place), switching, upon reaching the bottom of the hole, to a stable, cement-based grout prior to commencement of jetting. The grout fluid was mixed using a high shear colloidal mixing plant and transferred to the high pressure jet grout pump. Upon commencement of jetting, the grout was sent through high pressure hoses to the jet grout drill rig and through the drill rods to the tip of the drill string under a pressure of 400 bars before being ejected through one set of diametrically opposed jet grout nozzles. Simultaneously, compressed air was delivered through the rods to the nozzles, providing high pressure air surrounding the grout immediately upon its ejection through the nozzle, acting as a buffer between the jet-stream and any groundwater present. After crossing over to grout and pressurizing the system, the drill string was rotated and withdrawn by computer control, at the rotation and lift rates established from the test program. The pre-selected production parameters were constantly monitored, maintained, and recorded using the data acquisition (DAQ) system connected to the jet grouting apparatus.

The portion of ground above the elevation of the top of the jet grouted column remained untreated beyond assuring that it was appropriately backfilled with cement grout. During installation of the jet grout columns, the excess soil-cement waste material (spoil) was constantly evacuated from the hole via the annular space between drill rod and borehole wall.

![Figure 3: Plan of jet grout locations at EL. 222.64](image-url)
5.2 Initial Test Program

The primary goal of the initial test program was to confirm the optimal set of parameters (lift rate, rotation rate, grout pressure) for constructing soil-cement columns of known diameter and strength within soils representative of those present at the precise location of the sewer crossing. The secondary goal was to confirm the dimensions and reliability of the overlap between adjacent columns. The test program consisted of three jet grout columns, aligned vertically and overlapped as shown in Figure 4a. Existing grade at the test column location is 221.8 m. The 5 m long test columns were jet grouted from EL 213.8 m upwards to 218.8 m, with the uppermost 3 m untreated except for being backfilled with tremie placed cement grout prior to completely removing the drill string from the hole.

After waiting for 72 hours of undisturbed curing time, the test columns were evaluated in three ways, via exhumation for visual confirmation of constructed geometry, diamond coring to evaluate strength characteristics of overlapped and non-overlapped soil-cement, and probing to determine the lateral extent of treatment.

A trench box was used to allow for the exhumation of the upper 0.3 m of the test columns down to Elev. 218.5 m (Fig. 4b). Three core samples, drilled using the PQ-3 system, were obtained from the test columns. The locations of the cores were selected for evaluating the quality of the overlap between 2 columns, the overlap between 3 columns, and evaluating the strength characteristics of a portion of jet grouted column not overlapped, respectively. Probe holes, drilled using non-percussive rotary boring with water flush and a 115 mm drill bit, were put down at 4 different locations to determine the lateral extent of jetting.

Supplementing the post-installation evaluation of the test columns, unconfined compressive strength (UCS) testing was performed on grout samples obtained during jetting of the test columns, on spoil samples retrieved at the collar of the hole and on samples retrieved from coring.

All test results confirmed constructability using the proposed initial methodology and installation parameters. The average diameter of the exhumed columns was confirmed to be 2.6 m. UCS testing of core samples, including overlaps, met all specified criteria. Probe holes confirmed that soil-cement material was encountered up to 1.5 m from the centre of the columns. Based on the results of the initial test program, production jet grouting, using a design diameter of 1.2 m soil-cement column, was commenced.

5.3 Initial Installation

During installation of the first production jet grout column, JGC-12, movement was observed at the sewer and jet grouting was immediately stopped. The movement was detected after a 3.54 m long section of column JGC-12 was installed from EL 208.50 m to 212.04 m. After stopping, the contractor thoroughly examined the conditions at the sewer crossing location from data obtained during the partial installation of column JGC-12. Having analyzed the monitoring data in conjunction with the DAQ outputs from the jet grouting, it was determined that the movement of the sewer was a direct result of insufficient return of spoil to surface.

Potential modifications to the jet grouting installation methodology were reviewed in an attempt to establish the best suited approach to prevent any further movement of the existing sewer. Amongst the several possibilities for changes to the methodology, it was recognized that it would be most beneficial to find a way to change the installation method but maintain the parameters established during the comprehensive and successful testing already completed. A revised methodology,
incorporating the same parameters already proven by testing at this site, was proposed.

6 REVISED APPROACH TO JET GROUTING

6.1 Revised Methodology

The initial methodology incorporated an uncased 165 mm diameter drilled hole prior to jetting from the bottom upwards to EL 218.5 (Fig. 5a). The key modification to the revised approach was the installation of a sacrificial, 200 mm diameter x 4.7 mm wall thickness PVC casing to the full depth of the 300 mm diameter drilled hole prior to any jet grouting (Fig. 5b). All installation parameters remained unchanged. The idea behind the sacrificial casing was to assist in the evacuation of spoils by protecting the upper reaches of the hole from caving or “necking” and thereby restricting the flow of spoil to surface. To ensure the sacrificial casing did not inadvertently diminish the erosive effects of jetting, the lower extent of the sacrificial casing was pre-cut with partially circumferential slots to aid in its disintegration during jetting.

The modified installation sequence using the sacrificial thin wall PVC casing was performed as outlined below.

Step 1: Advance a 300 mm diameter hole to the target depth coincident with the planned underside of jet grout column (EL 208.5 m) using a drag bit and bentonite drilling slurry.

Step 2: Retract the drill tooling from the slurry-charged hole and install a thin wall (200 mm dia x 4.7 mm wall) PVC pipe, pre-cut with circumferential slots over its bottom 10 metres, extending the full depth of the hole all the way to surface.

Step 3: Grout the casing in place by injecting a cement-bentonite mix via tremie method, to the full depth of the hole, inside and outside the casing. Allow the casing grout to cure a minimum of 48 hours.

Step 4: Using non-percussive rotary boring with water flush, advance the jet grout string to the bottom (EL. 208.5 m) of the grouted, PVC-cased, hole and commence jetting using the same lift rate, rotation rate, injection pressure and grout mix that was used to construct the initial jet grout test columns.

Step 5: Stop jetting upon retraction to EL. 218.5 m (i.e. design top of column elevation).

Step 6: Remove drill string from the hole.

Before it could be implemented to construct production jet grout columns, the revised installation procedure required the installation and exhumation of a single supplemental test column to confirm that suitable geometric properties could be achieved by using the same jet grouting parameters.

6.2 Supplemental test program

A supplemental test program, consisting of installation of a single test column constructed using the revised methodology, was performed immediately adjacent to the location where the first test program was performed. The test column was installed next to the existing test area and with a minimum embedment depth of 7.4 m - tip elevation of 214.5 m or a distance of 3 x D below invert of existing sewer. A sacrificial thin wall PVC casing with slots within the jet grout zone was installed, with cement grout inside and out over the full depth of casing embedment, to a depth of 6 m and allowed to cure undisturbed for 48 hours. Jet grouting was performed from 7.4 m to 3 m below ground surface using the same jet grout parameters that were used for the initial test program.

Remnants of disintegrated PVC casing were present in the spoil pit after the supplemental test column was jet grouted (Fig. 6). The test column was exhumed 48 hours after its installation to confirm its diameter. A 1.6 m diameter column was achieved (Fig. 7) using the revised methodology, thereby confirming the appropriateness of the revised method for constructing overlapping jet grouted columns of design 1.2 m diameter.
Figure 5a: Initially proposed jet grouting methodology – uncased hole

Figure 5b: Revised installation methodology
QUALITY CONTROL AND QUALITY ASSURANCE

The quality control and quality assurance program was based on a combination of field observations, data acquisition (DAQ) system records, field sampling and laboratory analyses which are specific to jet grout column installation. QA/QC measures that exceeded the specified requirements were implemented.

8 RESULTS

The following results were obtained from the initial pre-production and supplemental test programs:

The following installation parameters were observed by the driller and recorded for each column by the DAQ system:

- Rotational speed of the drill string
- Lift speed of the jet grout monitor
- Grout slurry pressure and flow
- Air pressure and flow
- Volume of injected grout slurry

An installation report was submitted for each jet grout column at the end of each jet grouting shift.

The following quality control checks were performed on grout and spoils samples:

- The specific gravity of the grout and spoils were measured in accordance with the method described in API Recommended Practice 13B-1 with a mud balance.
- The Marsh time of the grout was measured in accordance with the method described in API Recommended Practice 13-1 with a Marsh funnel and a calibrated container.

The following quality assurance measures were employed:

- Unconfined compressive strength (UCS) testing was performed on spoil samples taken during the installation of the jet grout columns. UCS testing was performed in accordance with ASTM D2938.
- Core sampling was performed to evaluate the consistency of the jet grouted block. Coring was done using the PQ-3 system and the hole was advanced to the bottom of the jet grouted block. The cored hole was done at the centre of the overlap for columns JGC 12 & JGC 13 and the average core recovery was approximately 85%.
- DAQ records were reviewed daily to verify consistency of the jet grouting parameters versus time within the treatment zone.
Table 1.0: Results from the initial and supplemental test programs

<table>
<thead>
<tr>
<th>Test Program</th>
<th>Borehole within treatment zone</th>
<th>Jet Grouting Parameters</th>
<th>Specific Energy (MJ/m)</th>
<th>Soil-cement column diameter</th>
<th>7 days UCS of soil-cement (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-production</td>
<td>Uncased</td>
<td>Grout injection pressure (MPa)</td>
<td>40</td>
<td>0.25</td>
<td>237</td>
</tr>
<tr>
<td>Supplemental</td>
<td>Sacrificial perforated duct pipe</td>
<td>Grout injection pressure (MPa)</td>
<td>40</td>
<td>0.25</td>
<td>237</td>
</tr>
</tbody>
</table>

9 DISCUSSION

It is established practice within the jet grouting industry to construct pre-production test columns at every project unless the same specialist contractor has previously performed jet grouting at the same site and installed a test section (Burke, 2009). As profoundly valuable as the initial test program at this project proved to be, it still required the direct experience obtained from production jet grouting before the entirety of the information obtained from pre-production test work could be realized.

Challenges in ground improvement applications are common and specialty contractors must be in a position to address changes in a timely manner to meet the desired performance requirements. This case study demonstrates a systematic approach to address a challenging condition with an innovative solution. Additionally, jet grouting proved to be a versatile solution for in situ ground improvement at this project, considering the depth and constitution of the existing sewer, the location of the tunnel crossing within the roadway and the very soft materials within the treatment zone.

Jet grouting is considered as the most complicated grouting technology available and a high quality data acquisition (DAQ) system should be used and reviewed daily to assure that the work is being done properly (Burke, 2012). The contractor’s experience base and conditions encountered at this site proved valuable in implementing a suitable revised installation method. Jet grouting is a highly varied technology and there are many combinations available to create soil-cement elements to varying degrees of performance requirements.

10 CONCLUSIONS

Despite encountering challenging ground conditions at this site, installation of soil-cement columns using the double fluid jet grouting system was successfully completed to support the existing 750 mm diameter sewer pipe at its crossing of the proposed outfall alignment.

The initially proposed jet grouting methodology was based on standard industry practice and in full conformance with both the project jet grouting specifications and the ASCE Jet Grouting Guidelines (June, 2009), and was approved by the owner prior to commencement of production jet grouting. Despite this, problems were encountered that required changes due to grouting-induced heaving of the sewer. A significant amount of review and brainstorming was conducted to expeditiously develop a revised jet grouting installation methodology based on conditions encountered at the sewer crossing location.

Modification of the initial jet grouting approach resulted in the successful completion of jet grouting with no movement of the existing sewer, despite the close proximity of jet grouting to the sewer and the very soft clay (SPT ‘N’ = 0) present within the treatment zone. No similar application of sacrificial casing within the treatment zone for jet grouting applications is available in the literature to the best of the authors’ knowledge.

The modified approach was successfully implemented and all objectives of the jet grouting program were satisfied.
ACKNOWLEDGEMENTS

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REFERENCES


