A Case Study: Two-fluid jet grouting for Tunneling Application –
Soil stabilization and permeability reduction

Marcelo Chuaqui¹, Frank Hu², Naresh Gurpersaud² and Daniel Lees²

¹GeoSupprt Inc., Mississauga, ON, L5L 5M5, Canada
²Geo-Foundations Contractors Inc., Acton, ON, L7J 1W9, Canada

ABSTRACT: The York Durham Sewage System (YDSS) Interceptor Sewer construction spanned a total length of 5.5 km, which included a 1.4 km stretch of open cut construction and tunnelled stretch of 4.1 km, with four access shafts. Two of the tunnel access shafts were located in an environmentally sensitive area with water bearing cohesionless soils and considered as a potential geotechnical hazard for tunnel break-ins/break-outs. A combination of slurry wall and jet grouting was used to stabilize the ground and control groundwater flow at shafts #2 and #3, during break-in/break-out of the tunnel boring machine (TBM). This paper presents a case study, addressing the application of double fluid jet grouting technique to mitigate a significant geotechnical hazard at shafts #2 and #3 for the YDSS Interceptor Sewer Project.

INTRODUCTION

The York Durham Sewage System (YDSS) Interceptor Sewer construction spanned a total length of 5.5 km, which included a 1.4 km stretch of open cut construction and tunnelled stretch of 4.1 km. This interceptor sewer was constructed to provide relief to the YDSS through Richmond Hill, Ontario, Canada due to increasing development in surrounding areas. The tunnel depth varied between 9 m to 28 m below ground surface and comprised of 4 access shafts. Ground stabilization by jet grouting was required at two shaft locations due to water bearing cohesionless soils and the risk of significant ground loss into the shaft, upon break-in/break-out of the tunnel boring machine (TBM).

The double fluid jet grouting method was used to form complete, watertight and continuous soil-cement elements at shaft/tunnel junctions. The purpose of the jet grouting was to provide reduced permeability, stabilized soil at the tunnel break-in and break-outs at two shaft locations. The column diameter was expected to be 1.1 m with centre spacing of 0.8 m. Columns were installed in a primary, secondary and tertiary pattern.
This case history is presented from the perspectives of the specialty grouting contractor and the specialty grouting contractor’s consultant. The paper describes how a specific geometry, strength and permeability of treated soil were achieved and verified. References to lessons learned and specific challenges encountered on other two-fluid jet grouting projects performed in the Greater Toronto Area (GTA) are also made to assist in demonstrating or explaining a specific point or consideration.

A two phase test program was carried out. The first phase was to verify/optimize the design parameters to achieve the design column diameters. The second phase involved installation of a group consisting of 4 columns and to allow testing strength and permeability of a cluster of columns.

The quality control program, test program, designed and implemented jet grouting parameters, grout mix design and the verification program will be presented. Specific challenges such as maintaining spoils return, spoils management and protecting existing structures are also discussed.

BACKGROUND AND PROBLEM STATEMENT

The YDSS project included four locations where a closed-face tunnel boring machine (TBM) will enter the ground from inside an open shaft (break-out) or enter into an open shaft from the ground (break-in). At Shafts #2 and #3, blocks of jet grouting measuring approximately 9.3 m x 10.4 m x 9 m deep were required to provide soil consolidation and groundwater control during the sensitive mining operation. Figure 1 provides a layout of the tunnel and access shafts.

Jet grouting was performed to facilitate TBM shaft break ins/out at the vertical shafts. The specifications required jet grouted blocks outside the shafts with minimum jet grouted soil mass strength of 2MPa and average in-situ permeability of less than $1.0 \times 10^{-5}$ cm/s. The jet grouted blocks needed to extend 5.0 meters above/below and 6.0 meters laterally from the tunnel centerline. The selected option (i.e. jet grouting) allowed for a lower rate of dewatering for shafts and the least impacts to the Oak Ridges Aquifer Complex (ORAC) based on planned mitigation of dewatering at the shafts.

![Fig. 1. Layout of Access Shafts](image_url)
It was noted in the submittals that sampling by coring and compressive strength testing of core samples was not recommended as an effective test for determining an in-situ strength of 2 MPa. Sampling by coring provides disturbed samples with lower strength than the in-situ strength of the treated soil. Alternate strength confirmation methods were proposed, which consisted of casting samples from vented spoils and in-situ permeability tests.

**SUBSURFACE CONDITIONS**

The project site is located at the Oak Ridges Moraine of the York Region, near the major intersection of 19th Line and Leslie Road, north of Toronto, Ontario, Canada. The Oak Ridges Moraine was formed when the glaciers retreated from the area some 10,000 years ago. The host material for jet grouting at Shaft #2 consisted of moist to wet greyish-brown sand and silt with traces of clay forming faint layers and some gravel. This zone was referred to as the middle sand #2 layer. The shaft/tunnel junctions at Shaft #3 were located in material consisting of wet greyish-brown sand and silt with a trace of clay. The soil was classified as dense to very dense with N values of about 30. The ground water tables were located at 6.9 m below the surface at Shaft #2 and 2.0 meters below the surface at Shaft #3. Permeability of the soil before grouting was reported to be around $10^{-3}$ cm/sec.

The tunnel access shafts were constructed in the Oak Ridges Aquifer Complex (ORAC) within an area comprising of water bearing cohesionless soils with high groundwater table or artesian conditions. The volume of groundwater to be pumped at the tunnel shafts was substantially reduced compared with traditional methods by using the sealed shaft groundwater mitigating construction technique. A combination of a permanent slurry wall and jet grout groundwater cut-off was selected to be the most suitable method for the subsurface conditions according to Earth Tech (2005).

**JET GROUTING DESIGN CONSIDERATIONS**

The jet grouting works for the YDSS Project at Shafts #2 and #3 was performed by Geo-Foundations Contractors of Acton, Ontario, Canada in conjunction with Geo-Support Inc. (consultant). The double fluid system was selected to meet the requirements of the project based on soil conditions and requirements to reduce permeability.

There are two basic steps in the jet grouting process - drilling and grouting. The drilling method is selected according to the soil conditions, general site features and design specifications regarding hole depth and inclination (Xanthakos et al., 1994). The double fluid method uses compressed air to enhance the cutting effect of the jet. 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 turbulent action of the cut soil. The cut soil is more efficiently removed from the region of jetting by the bubbling action of the compressed air.
PRE-CONSTRUCTION TEST PROGRAM

A jet grouting test program was implemented at Shaft #2 to test the jet grouting procedure and verify the design assumptions for column diameter and in-situ characteristics such as strength and permeability of the jet grouting treatment zone. The test program consisted of two tests as follows:

1) The installation of three (3) jet grouted columns for verification of column diameter using different lift rates of 0.3, 0.45 and 0.6 m/min respectively. The jet grouting zone for the test columns started at 2.0 meters below surface elevation. The upper 2 meters of each column were carefully exhumed after 48 hours and the test results were used to select the parameters for production work.

2) The installation of a test group of four (4) interlocking columns using the same sequence and parameters selected for production work were used for the installation of the second set of test columns. Each column consisted of a jet grouted zone of 5.0 meters and the interlocking configuration was representative of the production work. Interlocked columns were cored and tested for permeability and samples of jet grout spoils were taken for unconfined compressive strength (UCS) tests.

A comparison of the jetting parameters used for the test program is presented in Table 1 along with data from two other locations in Toronto, Ontario. The specific gravity was measured using a mud balance and the diameter was measured after exposing the column. The jetting energy per meter versus the column diameters are illustrated in Figure 2.

<table>
<thead>
<tr>
<th>Test Col. ID</th>
<th>Press (MPa)</th>
<th>Flow (Lpm)</th>
<th>Lift (m/min)</th>
<th>Nozzle (mm)</th>
<th>Jetting Energy (MJ/m)</th>
<th>Grout W/C</th>
<th>Grout S.G.</th>
<th>Soil</th>
<th>Col. Dia. (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YD1</td>
<td>43</td>
<td>206</td>
<td>0.41</td>
<td>1X5.0</td>
<td>21.6</td>
<td>1.25</td>
<td>1.41</td>
<td>Sand and Silt N=9~47</td>
<td>1.40</td>
</tr>
<tr>
<td>YD2</td>
<td>43</td>
<td>214</td>
<td>0.26</td>
<td>1X5.0</td>
<td>35.4</td>
<td>1.25</td>
<td>1.41</td>
<td>Sand and Silt N=9~47</td>
<td>1.80</td>
</tr>
<tr>
<td>YD3</td>
<td>42</td>
<td>223</td>
<td>0.23</td>
<td>1X5.5</td>
<td>40.7</td>
<td>1.25</td>
<td>1.41</td>
<td>Sand and Silt N=9~47</td>
<td>1.40</td>
</tr>
<tr>
<td>YD4</td>
<td>43</td>
<td>335</td>
<td>0.23</td>
<td>1X5.5</td>
<td>62.6</td>
<td>1.25</td>
<td>1.41</td>
<td>Sand and Silt N=9~47</td>
<td>1.20</td>
</tr>
<tr>
<td>YD5</td>
<td>42.5</td>
<td>339</td>
<td>0.3</td>
<td>1X5.5</td>
<td>48.0</td>
<td>1.25</td>
<td>1.41</td>
<td>Sand and Silt N=9~47</td>
<td>1.85</td>
</tr>
<tr>
<td>YD6</td>
<td>42.2</td>
<td>339</td>
<td>0.39</td>
<td>1X5.5</td>
<td>36.7</td>
<td>1.25</td>
<td>1.41</td>
<td>Sand and Silt N=9~47</td>
<td>1.30</td>
</tr>
<tr>
<td>Site 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2C1</td>
<td>41</td>
<td>136</td>
<td>0.3</td>
<td>2X2.6</td>
<td>18.6</td>
<td>1.00</td>
<td>1.57</td>
<td>sand, N=14~46</td>
<td>1.2</td>
</tr>
<tr>
<td>T2C2</td>
<td>41</td>
<td>136</td>
<td>0.4</td>
<td>2X2.6</td>
<td>13.9</td>
<td>1.00</td>
<td>1.57</td>
<td>sand, N=14~46</td>
<td>1.1</td>
</tr>
<tr>
<td>T2C3</td>
<td>41</td>
<td>136</td>
<td>0.48</td>
<td>2X2.6</td>
<td>11.6</td>
<td>1.00</td>
<td>1.57</td>
<td>sand, N=14~46</td>
<td>0.9</td>
</tr>
<tr>
<td>Site 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3C1</td>
<td>22</td>
<td>124</td>
<td>0.2</td>
<td>2X2.6</td>
<td>13.6</td>
<td>1.00</td>
<td>1.57</td>
<td>Sand</td>
<td>0.9</td>
</tr>
<tr>
<td>T3C2</td>
<td>26</td>
<td>137</td>
<td>0.2</td>
<td>2X2.6</td>
<td>17.8</td>
<td>1.00</td>
<td>1.57</td>
<td>Sand</td>
<td>1.2</td>
</tr>
<tr>
<td>T3C3</td>
<td>30</td>
<td>145</td>
<td>0.2</td>
<td>2X2.6</td>
<td>21.8</td>
<td>1.00</td>
<td>1.57</td>
<td>Sand</td>
<td>1.5</td>
</tr>
<tr>
<td>T4T4</td>
<td>35</td>
<td>157</td>
<td>0.2</td>
<td>2X2.6</td>
<td>27.5</td>
<td>1.00</td>
<td>1.57</td>
<td>Sand</td>
<td>1.8</td>
</tr>
</tbody>
</table>
Notes:
2. YDSS test #11 is one (1) meter south of a 300mm diameter water main.
3. All test columns were jetted at 2 meters below ground surface.
4. Rotation speed between 18 and 20 rpm for all tests.
5. Energy = \( \frac{\text{flow rate} (\frac{m^3}{min}) \times \text{pressure} (\text{MPa})}{\text{lift rate} (\frac{\text{min}}{m})} \)

![Column Diameter vs. Energy](image)

**Fig. 2. Column Diameter vs. Jetting Energy**

The YDSS data is shown as two separate tests with nozzle diameters of 5.0 mm (YDSS-1) and 5.5 mm (YDSS-2). The data indicates that the 5.0 mm nozzles were more efficient than 5.5 mm nozzles at producing larger diameter columns. An anomaly in the 5.5 mm can be observed with an increased flow rate at the same lift rate that resulted in a smaller diameter column. For each test, the column diameter and energy share a fairly linear relationship. Based on experience, the relationship remains fairly linear within a certain parameter envelope. However, during jetting of excessively large columns a reduction in efficiency becomes apparent.

Based on data obtained from the test program, the following parameters were selected for production jet grouting:

- Neat cement grout w/c = 1.25 (Specific gravity = 1.4)
- Grouting pressure = 40 to 42 MPa;
- Nozzle diameter = 5.0 mm;
- Grouting flow rate = 270 to 280 l/min;
- Lift rate = 0.3 m/min
- Rotation speed = 18 to 20 RPM

The production column diameter was 1.5 m and columns were spaced at 1.2 meters apart. Theoretical grout per meter of column consumption was 1070 liters or 667 kg cement (Type 20 cement).

The second phase of the test involved confirming the treated soil properties with the selected jetting parameters and column spacing. This phase of the program involved...
jetting four interlocking columns with the same parameters and geometry as proposed for production jet grouting.

A test hole was cored at the centre of the interlocking block in order to check the properties of the soilcrete. Coring was done with a Longyear 38 drill using a diamond bit (HQ) and coring barrel. Additionally, in-situ permeability tests were performed by using a pneumatic packer inserted at 2 meters below grade. Water was pumped into the hole under pressure and the flow rate versus water pressure was measured during the test in order to calculate the permeability. The hole took no measurable amount of water during permeability testing.

PRODUCTION JET GROUTING

The rotary drilling method was used to advance the holes on this project. Alignment of the drilled hole was controlled by monitoring the display on the Jean Lutz (LT3) recorder, mounted next to the controls for the drill rig. Drilling to the target elevation was performed with grout injected at a low pressure and downward jetting to stabilize the hole. Figures 3 and 4 illustrate the layout of jet grouted columns at Shafts #2 and #3 respectively. Figure 5 shows a cross-section of tunnel axis at Shaft #3. The drill rig used was a Casagrande C-8 with a 24 meter mast extension. A Jean Lutz LT-3 jet grout logging system was used to display and record all jet grouting parameters in a real-time manner. Grout was prepared from an automated batch plant and pumped via a Metax MP-7 pump. Air was supplied through a 915 cfm compressor at working pressures of 12 to 15 bars.

The jet grouting product is underground and not visible from the surface, therefore it is critical to monitor and log the operational parameters for verification (i.e. matching parameters established during the test program). At the drilling stage, the Jean Lutz system logs the drilling penetrating rate, rod thrust pressure, rotation speed and mast inclination. This data can then be used to get a general insight on the soil profile. Should the soil condition significantly change with depth then a change in drilling parameters should be observed.

At the jetting stage, the Jean Lutz logs the grouting pressure and flow rate, air pressure and flowrate, lifting rate, rotation speed, and jetting duration time. This data can be easily verified to be within the established ranges. During the construction of one column, a leak in connection between two rods developed and the change in flow rate was immediately detected. The monitor was withdrawn and the situation was corrected in a timely manner. Figure 6 shows a typical output from the Jean-Lutz automatic parameter recorder.

The Jean Lutz recorder can log the injection parameters; however, it is necessary to also monitor the spoils venting. The jet grouting method relies on the spoils being able to vent to surface freely. If the annulus around the drill rods becomes plugged, the area around the nozzles becomes pressurized, resulting in loss of energy from the soil erosion process and more importantly, potential damage to neighboring structures due to hydrofracture and hydraulic jacking. It is impractical to measure the ejected spoils quantitatively but it is relatively easy to estimate the flow as full, ¾, ½, ¼, or zero. The spoil density was periodically measured using a mud balance to track variations in composition of spoils (Table 2).
The spoils were sampled and cylinders cast for compressive strength testing. The cylinders were filled with spoils typically in lifts and tamped to avoid air pockets and stored in an area to avoid disturbance. This sampling method is an indication of the material but may not be an accurate representative especially if mixing is poor. As mentioned coring is typically intrusive and destructive so if strength is a key parameter other means such as pressuremeter testing may be used.

Fig. 3. Layout of Jet-Grouted Columns at Shaft #2

Fig. 4. Layout of Jet-Grouted Columns at Shaft #3
Table 2. Spoil Densities Measured from the Ejected Spoil at the YDSS Project

<table>
<thead>
<tr>
<th>Column I.D.</th>
<th>Measured spoil density (g/cm³)</th>
<th>Comment</th>
<th>Jet grouting date</th>
</tr>
</thead>
<tbody>
<tr>
<td>YDSS Shaft #2, Test #7</td>
<td>1.90</td>
<td>No adjacent columns were grouted</td>
<td>April 12, 2007</td>
</tr>
<tr>
<td>YDSS Shaft #2, Column A-3</td>
<td>1.97</td>
<td>Adjacent column B3 was grouted 24 hrs before</td>
<td>April 23, 2007</td>
</tr>
<tr>
<td>YDSS Shaft #2, Column A-1</td>
<td>1.92</td>
<td>Adjacent column B1 was grouted 24 hrs ahead of time</td>
<td>April 24, 2007</td>
</tr>
<tr>
<td>YDSS Shaft #2, Column L-5</td>
<td>1.90 /2.02</td>
<td>No adjacent columns were grouted. Samples taken from the top and bottom respectively from the ejected spoil flow.</td>
<td>April 24, 2007</td>
</tr>
<tr>
<td>YDSS Shaft #2 A-2</td>
<td>1.88</td>
<td>Adjacent columns A1, A3 and B1 were grouted 24 hrs ahead of time</td>
<td>April 25, 2007</td>
</tr>
<tr>
<td>YDSS Shaft #2 C-2</td>
<td>1.94</td>
<td>Adjacent columns C1, C3, B1 and D2 were grouted 24 hrs ahead of time</td>
<td>April 25, 2007</td>
</tr>
<tr>
<td>YDSS Shaft #2 F-1</td>
<td>1.87</td>
<td>Adjacent columns E1, E2 &amp; G1 were grouted 24 hrs ahead of time</td>
<td>May 3, 2007</td>
</tr>
<tr>
<td>YDSS Shaft #3 I-1</td>
<td>1.92</td>
<td>No adjacent columns were grouted</td>
<td>May 22, 2007</td>
</tr>
<tr>
<td>YDSS #3, D7a</td>
<td>1.55</td>
<td>All adjacent columns grouted 24 hrs ahead of time</td>
<td>May 29, 2007</td>
</tr>
<tr>
<td>YDSS Shaft #3 G3</td>
<td>1.92</td>
<td>Adjacent columns G4, F3, H2, H3, H4 were grouted 24 hrs ahead of time</td>
<td>May 29, 2007</td>
</tr>
<tr>
<td>Sterling Road P3</td>
<td>1.86</td>
<td>P1 and P2 were grouted 24 hrs ahead of time</td>
<td>Nov, 2010</td>
</tr>
</tbody>
</table>

Note: Injected grout S.G. =1.41 at YDSS and S.G.=1.57 at Sterling Road.
Fig. 6. Typical Jet-grouted Digital Log from Jean Lutz Monitor

The spoil densities stayed above 1.90 g/cm³ for most of the columns but dropped as surrounding columns were installed.

At the start of production jet grouting a primary-secondary-tertiary-quaternary (P,S,T,Q) sequence was followed, but very soon, it became apparent this was not practical due to the working area being very tight making rig movement time consuming. In order to improve productivity, a fresh column to fresh column based sequence was implemented. Most of the new columns were jet grouted while the adjacent columns were freshly installed (i.e. less than 24 hours curing time).
High production rates were achieved with the rod carousel and the 24-meter lattice mast extension on the C-8 drill rig. This allowed for fast drill down times and for the columns to be constructed in a single stroke without stopping for removal of rods during column jetting operation.

The capabilities to store grout in a large 7 cubic meter agitator and to batch grout quickly were important in allowing columns to be constructed without interruption.

At Shaft #2, a total of 75 columns were jetted in 14 working days, with an average rate of 5.4 columns per day. At Shaft #3, a total of 149 columns were jetted in 20 working days, with an average production rate of 7.45 columns per 10 hour working day.

QUALITY ASSURANCE/QUALITY CONTROL

The following components of the construction methodology assisted in maintaining quality of the finished product:

- Careful planning of the general site arrangement, including allowing for cement delivery, spoils containment and spoils storage/disposal.
- Pre-production test programs to establish the drilling and jetting parameters.
- Confirmation of verticality and ensuring a stable footprint for the drill rig. Verticality was tracked and adjusted through the Jean Lutz monitoring system.
- Control of the batching operation including measurement of specific gravity of the grout and recording of each batch mixed.
- Used lattices to extend the drilling mast in order to ensure continuous jetting operation.
- Incorporated large grout holding tank to supply sufficient grout during jetting.
- Computerized logging and display of jetting parameters for easy verification.
- Checked spoil and air returning during jetting and taking grout and spoil samples periodically.
- Post-production test program to check the soilcrete strength, integrity and permeability.

POST CONSTRUCTION VERIFICATION PROGRAM

The post construction verification program included coring to check integrity, unconfined compressive strength testing of spoils samples to confirm strength and in-situ water pressure testing to check the permeability of the grouted zone (Table 3). Core holes #1 and #2 were performed at the center of the interlocked columns in the test zone and core holes #3, #4 and #5 were performed within the grouted production zone. In-situ water test showed that the treated zone had a permeability of less than \(10^{-5}\) cm/sec. Many of the boreholes took no measurable quantity of water over a 5 minute interval. Testing was conducted at an effective pressure of 1 psi per foot depth. Table 3 shows the unconfined compressive strength testing results. Figure 7 shows the TBM during break-in at Shaft #3.
Table 3. UCS Test Results of Spoil Samples

<table>
<thead>
<tr>
<th>Date of sampling</th>
<th>Location of sampling</th>
<th>Sample Cylinder#1</th>
<th>Sample Cylinder#2</th>
<th>Sample Cylinder#3</th>
<th>S.G. from spoil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Curing time (days)</td>
<td>UCS (MPa)</td>
<td>Curing time (days)</td>
<td>UCS (MPa)</td>
</tr>
<tr>
<td>24-Apr-07</td>
<td>Shaft #2, Pile A-1</td>
<td>7</td>
<td>3.7</td>
<td>28</td>
<td>7.2</td>
</tr>
<tr>
<td>25-Apr-07</td>
<td>Shaft #2, Pile A-4</td>
<td>7</td>
<td>2.7</td>
<td>28</td>
<td>5.9</td>
</tr>
<tr>
<td>26-Apr-07</td>
<td>Shaft #2, Pile D-5</td>
<td>7</td>
<td>3.9</td>
<td>28</td>
<td>4.8</td>
</tr>
<tr>
<td>27-Apr-07</td>
<td>Shaft #2, Pile J-4</td>
<td>7</td>
<td>2.3</td>
<td>28</td>
<td>4.5</td>
</tr>
<tr>
<td>28-Apr-07</td>
<td>Shaft #2, Pile K-4</td>
<td>6</td>
<td>4.1</td>
<td>30</td>
<td>9.6</td>
</tr>
</tbody>
</table>

Notes:
1. Samples were taken from the spoil around the columns during the time of jetting.
2. Sample cylinder size dia.=76mm H=152mm.
3. Grout W/C=1.25 by weight. Type 20 cement used.

CONCLUSIONS

The following conclusions can be drawn from this case study:
- Jet grouting is an effective ground modification technique to stabilize problem soils and provide containment of ground water.
• The unconfined compressive strength (UCS) of the jet-grouted soil ranged from 4.6 MPa to 9.7 MPa after 28 days compared to a specified minimum of 2MPa.
• The average in-situ permeability of the jet grouted column was less than 1 x 10^{-5} cm/sec.
• A well-structured quality control/quality assessment program is vital for an effective jet grouting project.
• The Jean Lutz LT3 data acquisition system provided invaluable information to verify the injection parameters and evaluate the effectiveness of production work on a real time basis.
• Column location and alignment are important aspects in the execution of a jet grouting project.
• A field trial must be performed for each jet grouting project in order to evaluate the effectiveness of the equipment and the selection of the appropriate injection parameters.
• A specific jet grouting energy of 37.3 MJ/m created an average soilcrete column of 1.5 m diameter within the limits of the subsurface conditions at the YDSS Project.

REFERENCES