The West Toronto Diamond project, under construction since 2006 and due to be complete in 2015, is a rail-to-rail grade separation project in the heart of urban Toronto. Once complete, a depressed corridor over 1000 metres long will take the CN tracks beneath the CPR tracks. An interlocking steel pile wall serves to retain ground and cut off groundwater. Remedial measures, constructed using jet grouting, were required at several locations within and behind the steel piles.

At mechanical interlock joints damaged or suspected of being damaged, jet grouting was used to improve native soils on the retained side of the wall to reduce permeability of the soil mass in intimate contact with the joints to $10^{-7}$ cm/s. At a number of steel piles where groundwater and soil type combined to cause basal instability inside the pipes during the interim between excavation and concreting, jet grouting was used to construct temporary bottom seals. At locations near adjacent structures where the steel pile installation process resulted in disturbed ground on the retained side of the wall, jet grouting was used to strengthen and stabilize ground.

This paper outlines the details of the various jet grouting applications, the respective testing programs implemented to demonstrate in situ permeability and strength of the soil-grout matrix, and performance of the constructed system.

INTRODUCTION

The West Toronto Diamond (WTD) is a junction of several railway lines, all intersecting at the same grade (Figure 1). A major grade separation project at this site commenced in 2006 and is scheduled to be completed in 2015. The whole of the work is comprised of multiple contracts, completed and/or ongoing, by different constructors. Once completed, a depressed corridor over 1000 metres long with over 23,500 m$^2$ (face area) of retained earth will bring the CN tracks beneath the CPR tracks and eliminate a major bottleneck at the most heavily used rail crossing in Canada.

The principal component of the work is construction of a new interlocking steel pile wall that will serve as both a retaining wall and a hydraulic barrier to isolate the new depressed corridor from the high groundwater table present within the retained ground. The interlocking steel pile wall was constructed using two different techniques consisting, in simplified terms, of piles driven in place and piles pressed in place. Significant portions of wall required remedial measures for various reasons resulting from wall installation challenges. Jet grouting – sometimes for permeability reduction only, sometimes for soil strengthening only, sometimes for a combination of both – was used to complete remedial measures over a significant portion of the interlocking steel pile wall.
BACKGROUND

The WTD dates back to the first days of the national railways at the closing decades of the 19th century, and has long been a bottleneck for commuter and freight rail traffic. Toronto’s successful bid to host the 2015 Pan Am Games has spurred significant transportation infrastructure investment, and completion of the WTD grade separation is an integral component of the master renewal plan that will open the way to several improvements that could not otherwise be realized.

The interlocking steel pipe retaining wall that was installed to permanently retain up to 12 metres of cut along the depressed corridor was selected for its ability to act as a hydraulic barrier during and after construction. The pressed in place version of this piling system was developed in Japan and was new at the time to the Ontario market (Archibald et al., 2007). The wall consists of 914 mm diameter steel piles coupled to one another via mechanical joints referred to as P-T interlocks (Fig. 2). After installation of its adjacent host piles, the P-T interlock is designed to be cleaned and filled with bentonite-cement grout in order to render the wall joints impermeable.

Installation of the interlocking steel pipe pile wall took place from 2006 to 2011 under multiple contracts completed by different constructors. Although the work was tendered on the basis that all piles be installed using the pressed in place Giken method, the majority of the piles were driven or oscillated in place as a result of a contractor-proposed alternate. Only a small portion of interlocking steel piles were pressed in place. Remedial work, performed using jet grouting and broken out under three different subcontracts referred to as JG-A, JG-B and JG-C, per Table 1.0, was required at significant portions of wall constructed using both driven/oscillated and pressed in place installation methods.
Figure 2: Plan layout of interlocking steel pile wall including P-T Interlocks

Table 1.0 – Summary of jet grouting at WTD

<table>
<thead>
<tr>
<th>Subcontract</th>
<th>Location</th>
<th>Pile Installation Method</th>
<th>Jet Grouting Process</th>
<th>Geometry</th>
<th>Elevation extent of grouting</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>JG-A</td>
<td>STN. 100 + 173 to 101 + 125</td>
<td>Driven</td>
<td>Double Fluid</td>
<td>Ø1200 mm Circular column, tangent</td>
<td>El. 103 to El. 117</td>
<td>5300 lineal metres</td>
</tr>
<tr>
<td>JG-B</td>
<td>STN. 100 + 720 to 100 + 975</td>
<td>Pressed In</td>
<td>Double Fluid</td>
<td>Half-column; radius = 600 mm</td>
<td>El. 101 to El. 117</td>
<td>2656 lineal metres</td>
</tr>
<tr>
<td>JG-C</td>
<td>STN. 100 + 740 to 100 + 905</td>
<td>Driven and Pressed In</td>
<td>Double Fluid</td>
<td>Ø900 mm Circular column, concentric</td>
<td>El. 100 to El. 102.5</td>
<td>147 each</td>
</tr>
</tbody>
</table>

**SUBSURFACE PROFILE**

Surface elevation of the site varies between 119 and 122.0 m (geodetic). The subsurface material present within the jet grout project area is comprised of 1 to 3 m of fill underlain by native deposits of clayey-silt to silty-clay, sand to sand and silt and clayey-silt to silty clay till (Fig. 3). A dense clay till layer underlays the entire site at Elev. 103 (GBR, 2008). Ground water level varies from 4 to 5 m below existing grade. The groundwater level at the site fluctuates as a result of seasonal variations in precipitation, runoff and temperature. At the deepest retained profile, pile depths extend to Elev. 101 and are toed into the clay till. Once complete, the lowest elevation of the depressed corridor will be at Elev. 112.0 (with temporary excavation within the corridor to Elev. 110.0), well into the water bearing sand to sand and silt deposits. Approximately 550 lineal metres of the 1000 metre long depressed corridor will be below the groundwater table.
Figure 3: Subsurface profile with jet grouting scopes superimposed
SUBCONTRACT JG-A: DAMAGED P-T INTERLOCKS

Overview

After completion of the first major pile installation phase, a significant number of pipe piles and interlocks were known to be damaged, and there was sufficient evidence to suggest that an additional significant number of interlocks were potentially damaged. Consequently, a new pile validation contract was awarded in 2010 to extract and replace damaged piles, and based on data gathered during validation work, a new subcontract (Contract JG-A) was awarded for jet grouting to repair P-T interlocks suspected or known to be damaged and leaking.

The specifications required the design, means and methods and provision of all equipment, materials and labour for sealing of P-T interlocks determined to be leaking or with the potential to leak as a result of damage during installation. Sealing of P-T interlocks was required to be completed from the soil side of the interlocking steel pipe pile retaining wall and drilling or other penetration of the steel pipe piles and existing interlocks was not permitted. Grouting or other pressure injection of fluid or viscous materials to perform the work must not fracture the ground vertically or horizontally, and it was required that the repair method result in a material with a measured in-place permeability of $10^{-7}$ cm/s or less, covering the external width of the P-T interlock joint by at least three times the joint width and an equivalent radial thickness as measured from the nearest edge of the joint opening. Additionally, all repaired joints must not exhibit visible or measurable leakage of water under a minimum water pressure equal to 80 kPa one week following sealing and forever thereafter.

Jet grouting is a ground modification system used for the in situ mixing of soils with a stabilizer (typically neat cement grout) injected at very high pressures (up to 600 bar) through small diameter nozzle(s). The grout is injected at high velocity, enabling the jet grouting process to destroy the natural matrix of the soil and create a mixture of the stabilizer with the in situ soils (Burke, 2009). When parameters such as lift rate, rotation speed, injection rate and injection pressure are optimized, the result is a homogenous and continuous structural element with determinable strength and permeability characteristics (Gurpersaud et al., 2013); (Burke, 2012). Jet grouting is regarded as one of the most versatile ground improvement systems which can be used to strengthen soil, cut off groundwater and provide structural rigidity with a single application (Moseley and Kirsch, 2004). Jet grouting can be applied to a wide range of soils from non-cohesive, poorly graded granular soils to cohesive plastic clays.

The double fluid jet grouting process was proposed for WTD subcontract JG-A to construct the specified low permeability seal at the damaged P-T interlocks. The double fluid method employs a two-phase internal rod system for the separate supply of grout and compressed air via separate concentric nozzles. Injected simultaneously, the grout jet both erodes and mixes the soil, while the compressed air is injected in a shroud surrounding the grout jet to amplify the erosive characteristics of the cement grout stream. The contractor-designed scheme consisted of installation of continuous vertical jet grout columns, in intimate contact with existing P-T interlocks, from 15 m below surface to 3 m below surface (Fig. 4), to provide the specified coverage and permeability.
A pre-production test program was required to confirm the geometric properties and in situ permeability of the jet grout columns. The contractor’s proposed test program included installation of 3 jet grout columns to demonstrate conformance with the specifications. Challenges related to directly verifying in situ permeability significantly altered the pre-production testing and resulted in several weeks of testing, over 3 phases, using a variety of methods, and a final total of 14 test columns.

Phase 1 test columns were installed at the centre of the East Corridor (south end). The quantity of columns grew from 3, as originally intended, to 6 in order to evaluate a wider range of jet grouting parameters. Per industry standard practice, testing of Phase 1 columns was completed in general conformance with the ASCE Jet Grouting Guideline (2009). In situ permeability testing was performed on two test columns in holes advanced by HQ-3 coring at columns TC-1 and TC-4, at 0.3 m and 0.15, respectively, from the centre of the columns. Despite much evidence to suggest that the target permeability was being achieved, including lab testing of spoil samples to $10^{-8}$ cm/s permeability, good exhumed geometry and multiple field results to $10^{-6}$ cm/s, direct confirmation of constructed jet grout test column permeability meeting the specified criterion was not achieved.

When the in situ permeability could not be directly demonstrated, a next testing phase, Phase 2, was undertaken consisting of 8 test columns installed adjacent to the East Wall (west side). Phase 2 test columns were offset 0.5 m from the centre of the P-T interlock and were constructed from Elevation 119.0 m and jetted from Elevation 115.0 m to 110.0 m. Permeability testing methodology was modified to avoid the destructive action of coring. A 108 mm ID steel conductor pipe was pressed in place at the centre of each test column installed during Phase 2 to approximately 6 m below ground surface. The columns were allowed to cure for a week before the test hole was advanced, via drilling with a 50 mm diameter bi-cone drill bit with water flush to 1 m below the steel conductor pipe. Despite this revised approach, Phase 2 test columns still could not directly demonstrate achieving the target in situ permeability.

The final phase of pre-production testing, Phase 3, was performed on 2 production jet grout columns. A steel conductor pipe was installed coincident with the central axis of the freshly installed column (Fig. 5). This pipe was installed to function as a conductor pipe to perform in situ permeability testing. Spoil samples were also taken for laboratory permeability testing.

A modified procedure was used for the development of the test hole by using a forming process rather than a drilling method. The modified method eliminated several uncertainties associated with destruction.
resulting from drilling of a test hole in the relatively weak soil-grout matrix. After setting the conductor pipe in place, an inner 50 mm diameter steel pipe with an end plug was installed to 1 m below the tip of the conductor pipe. The inner pipe was rotated periodically and remained in place until just prior to initial set of the jet grout matrix. Thankfully, the test hole was successfully developed, but only after a significant amount of care and monitoring to establish a suitable time for the removal of the inner pipe.

Production work

Several challenges were encountered during production work due to the access constraints, rail traffic, adjacent properties and scheduling conflicts arising from multiple owners of the railways.

The scope of work for P-T interlock repair was developed during the initial phase of production work since the validation work was ongoing. As damaged and potentially damaged interlocks were identified, the owner identified treatment zones for each respective work area. During production jet grouting, quality control consisted of data acquisition, real-time checks on grout using a mud-balance and Marsh Funnel, and spoil sample casting for laboratory testing of unconfined compressive strength and permeability.
In stark contrast to the highly negative experience of various stakeholders on and surrounding the site resulting from the high energy driven pile installation method, all jet grouting was completed without excessive noise or vibration.

In total, over 5300 lineal metres of jet grout columns were constructed under subcontract JG-A.

**SUBCONTRACT JG-B: SOIL STRENGTHENING AT NRT BUILDING**

**Overview**

In 2009, after the driven method difficulties were known, the pressed in place method was used to install steel piles along a 350 m long stretch of wall in front of the National Rubber Technologies (NRT) building where the sensitive condition of the existing spread foundations motivated the owner to preclude driving or oscillating as pile installation options. The average distance from the centre of the steel pile wall to the rear wall of the NRT building is 3.5 m. Although the pressed in place method was implemented over this portion of the work, the piles could not be advanced without the aid of augering and washing ahead of the leading edge of the open-ended steel piles. This method resulted in the successful installation of the steel piles, but at the known cost of disturbing the ground on all sides of the piles over the full depth of pile. Due to concerns that the disturbance would result in settlement of the retained NRT building once the depressed corridor was excavated, a new jet grouting subcontract (Contract JG-B) was awarded to strengthen the disturbed soils in order to mitigate the likelihood of movements and settlement of the NRT building.

**Test program**

The preliminary jet grouting parameters remained the same as those developed and confirmed in JG-A. In order to minimize the effects of the jet grouting on the NRT building, a modified jet grout column geometry consisting of semi-columns was implemented for the purpose of targeting the P-T interlocks while leaving a wedge in place between the wall and the building. Since a different geometry was used relative to earlier tests, additional test columns were installed to verify the constructed geometric profile. The geometric properties of the test elements were successfully verified via exhumation at a test location comprised of suitably representative materials.

**Production work**

In order to prevent heaving and/or settlement of the NRT building, a slightly modified jet grout installation approach was implemented. Prior to commencement of jet grouting, 250 mm diameter PVC conductor pipes were pre-installed from existing grade to the top of treatment zone and grouted in place using a cement-bentonite grout. The pipes functioned as a conduit for spoils from the treatment zone to the surface and reduced the risk of heaving or spoils migrating to the underside of the NRT building. Approximately 3380 lineal metres of jet grouting was completed adjacent to the NRT building.

**SUBCONTRACT JG-C: TEMPORARY BASE SEALS AT SELECTED PIPE PILES**

**Overview**

The permanent wall configuration consists of steel piles, driven to Elev. A (typically EL.101 m) and filled with reinforced concrete to Elev. B (typically EL. 107.9 m) as shown in Figure 3. Both Elev. A and B are functions of retained depth. The construction process includes removal of soil (by augering) within the steel pile down to Elev. A for the subsequent installation of concrete (unreinforced and reinforced). Over the worst stretch of wall in terms of soil type, gradient and clean-out depth, basal instability in the interim between completion of augering and commencement of concreting manifested itself at several locations. A new subcontract (Contract JG-C) was awarded to construct temporary, 1.5 m deep base seals inside selected steel piles extending to 1 m below Elev. A.

**Production work**

No test program specific to bottom sealing was undertaken. Wherever jet grouted bottom seals were required, all piles were pre-augered to a depth of approximately 14 m prior to commencing installation of the jet grout plugs. A template/guide frame was used to centralize the jet grout drill string at depth inside the steel pipe piles. All spoils from the jetting process were contained inside the steel piles and left to
strengthen in the interim between jetting and subsequent drilling for concreting. This approach was used to minimize the risk of fouling the adjacent tracks, both during jet grouting and during subsequent clean out. In total, 147 piles were constructed with the help of temporary jet grouted bottom seals.

DISCUSSION

Although jet grouting was a well established product in the Greater Toronto Area by the time of the first jet grouting work at this project, the high profile of the project and the remedial nature of the work meant that the work was under intense scrutiny by multiple stakeholders. Successfully demonstrating conformance with the specifications was especially imperative, but the $10^{-7}$ cm/s criterion, as detailed above, was significantly difficult to demonstrate.

For this reason, it was essential to gather as much information as possible during installation and testing of the jet grout test columns. The testing approach had to be modified several times based on the conditions encountered at the site and lessons learned as the installation and testing progressed.

In situ permeability testing of jet grouted columns is notoriously difficult, and the testing gets progressively more difficult as the target permeability decreases. Creating a cavity within the heart of a jet grouted column can be done either by casting the cavity after the jet grout has gelled (but before it has strengthened), or by drilling the cavity into an already strengthened column. Both approaches are susceptible to having non-representative boundary conditions (such as radial shrinkage cracking extending inwards from the outside of the column to the wall of the cavity) influence the permeability testing results. In the case of casting, the column must be treated at precisely the right time: too early will result in a collapsed cavity, too late and the column will be too strong to cast any size of cavity let alone the intended size. In the case of drilling, this is a highly destructive process, all the more so because jet grouted columns, and especially low permeability jet grouted columns with high bentonite content, are not particularly strong to begin with. The pressure at which the external flush process water must be applied during diamond core drilling, is, by itself, enough to cause microfracturing within the column. There is also a high probability of mechanical damage attributable to the diamond core barrel’s natural chattering during drilling and a risk of rupture due to methods employed to ensure retrieval of the core itself.

In cases where low permeability is sought to be proven, the element of time plays a large role as well. The test must either be done using hydrostatic head and be conducted over several days (during which time atmospheric effects such as temperature and evaporation must be measured to a precise degree) or be done using an applied over-pressure which itself runs the risk of hydrofracturing the jet grout column.

As detailed above, the initial testing program was drawn out over several weeks, perhaps unnecessarily, and certainly at a significant cost to the project, because of the incompatibility between the specifications and the realities of permeability testing of jet grouted soils. It got to the point during testing where everyone – owner’s consultant, contractor, contractor’s specially hired consultant – agreed that the target permeability must actually be present in situ despite the inability to directly demonstrate this truth. For future projects where permeability is required, the WTD example may prove as a practical example for calling up a tight permeability but relaxing the degree to which said permeability must be directly demonstrated. Additional details pertaining to the test program such as jet grouting parameters, permeability and grout mix design are presented in Gurpersaud et al., 2012.

CONCLUSIONS

Jet grouting was successfully implemented at the West Toronto Diamond grade separation project to solve a variety of conditions requiring remedial improvement of native soils for the purpose of permeability reduction and soil strengthening.

Extensive testing, consisting of multiple field trials and laboratory testing of wet grab samples and spoil samples, was successfully completed to verify the in situ permeability, unconfined compressive strength and geometric properties of jet grouted columns installed at the West Toronto Diamond site.

Jet grouting resulted in no detrimental effects resulting from high vibration, in stark contrast to
earlier works undertaken at the same site. All jet grout elements were constructed within a highly congested site, to a high level of construction safety compliance and without significant impact to ongoing, continuous railway operations.

Despite exhaustive attempts to do so, the jet grouting constructor could not directly prove in situ permeability of $10^{-7}$ cm/s, despite being able to make a strong case – indirectly – for this criterion being met. An advancement would be achieved if the specified jet grout column permeability could be directly verified.

ACKNOWLEDGEMENTS

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REFERENCES


