



## An extensive jet grout test program for a low permeability barrier

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### ABSTRACT

An extensive jet grout test program was performed at the West Toronto Diamond Rail-to-Rail Grade Separation Project in Toronto, Ontario by Geo-Foundations Contractors Inc. Double fluid jet grouting was used to create a low permeability soil-cement matrix to seal damaged and potentially damaged piling joints. In order to establish conformance with the specifications, several phases of testing were conducted to verify jet grouting design parameters required to achieve the specified in situ permeability criteria of  $1 \times 10^{-7}$  cm/s. Despite the fact that only three test columns were initially contemplated to verify column geometric properties and in situ permeability prior to production jet grouting, procedural challenges and the severity of the performance threshold necessitated the construction of fourteen test columns. A wide range of lift rates and variations in grout mix designs were utilized for installation of the test columns in order to determine the optimal parameters. This paper summarizes the various test programs, laboratory and field testing, jet grouting parameters, subsurface conditions and modifications to the testing methodology undertaken at the West Toronto Diamond project.

### RÉSUMÉ

Un vaste programme de test de coulis de jet a été réalisée au Projet West Toronto Diamond Rail-à-Rail-mouton à Toronto, en Ontario, par Geo-Foundations Contractors Inc. Double jet grouting de fluide a été utilisé pour créer une matrice de ciment du sol à faible perméabilité pour sceller endommagé et potentiellement endommagées joints s'accroissent. Afin d'établir la conformité avec les spécifications, plusieurs phases de tests ont été effectués pour vérifier coulis paramètres de conception d'avions nécessaires pour atteindre le spécifié dans les critères de perméabilité in situ de  $1 \times 10^{-7}$  cm / s. Malgré le fait que seules trois colonnes d'essai ont été initialement envisagées pour vérifier colonnes propriétés géométriques et de la perméabilité in situ avant la production jet grouting, les difficultés de procédure et de la gravité du seuil de performance nécessita la construction de quatorze colonnes de test. Une large gamme de vitesses de levage et des variations dans la conception des mélanges de coulis ont été utilisés pour l'installation des colonnes de test afin de déterminer les paramètres optimaux. Ce document résume les différents programmes d'essais, essais en laboratoire et sur le terrain, les paramètres de jet grouting, les conditions du sous-sol et des modifications à la méthodologie des tests entrepris sur le projet West Toronto Diamond.

### 1 INTRODUCTION

The West Toronto Diamond (WTD) is a junction of railway lines owned by Canadian National Railway (CN) and the Canadian Pacific Railway (CPR), located in Toronto, Ontario (Fig. 1). This at-grade crossing is considered the busiest rail intersection in Canada. Begun in 2006, multiple contracts by multiple constructors have been undertaken to construct a grade separation in order to eliminate the at-grade diamond crossing. Once complete, the CN tracks will be depressed relative to the CPR tracks; the grade separation works are over a kilometre long.

Construction is being performed within a complex and congested area, with regular railway operations maintained throughout, and requiring coordination with the four property owners (CPR, CN, Toronto Terminal Railway and City of Toronto). Within the limits of the construction area there are also four operating railways – CPR, CN, GO Transit and Via Rail.

During an earlier contract, an interlocking steel pipe pile cantilever retaining wall was installed to permanently retain the existing grade in the vicinity of the proposed

depressed corridor. The wall consists of 916 mm diameter steel piles (some pressed in place, most driven by pile driver or oscillator) with mechanical joints referred to as P-T interlocks (Fig. 2). This particular piling system was deemed advantageous because, as well as retaining the proposed cuts, it provided the means by which ground water could be cut off from passing through the wall into the depressed corridor. During pile installation, several of the interlocks were damaged, thereby compromising the ability of the mechanical connection to perform as a permeability barrier. In order to remediate damaged joints, a method to create a low permeability seal on the outside of the joints was required. At this stage of construction, a new subcontract was awarded for the design and installation of a jet grout cut-off scheme using double fluid method with a cement-bentonite grout mix.

In support of the contractor-designed jet grouting scheme, an extensive jet grout test program was conducted at the West Toronto Diamond in order to establish design parameters for constructing low permeability jet grout columns. The principal objectives of the test program were to verify column diameter and to conduct in situ permeability testing to ensure that the

residual permeability of the treated ground satisfied the specified criteria. In total, fourteen pre-production jet grouted test columns were installed over three phases in order to confirm jet grouting parameters prior to commencement of production jet grouting work.

## 2 BACKGROUND

The WTD project commenced in 2006 and is scheduled to be completed in late 2014. GO Transit's Georgetown rail service currently operates along the CN line and crosses two CPR lines at the same grade. Once completed, the grade separation will bring the CN tracks beneath the CPR tracks, resulting in the elimination of a major bottleneck at the most heavily used rail crossing in Canada. The project will also result in improved service reliability, reduce noise levels and allow for future service improvements in the Georgetown South rail corridor. Elimination of this bottleneck is also a key component of the new Union Pearson Express between Toronto's Union Station and Pearson International Airport.

The scope of the project includes new rail alignments for the two-track (future four tracks) CN Weston Subdivision; temporary rail alignment detours for CN and CPR tracks; two new bridges to carry Old Weston Road and the CPR Mactier wye tracks over the depressed CN Weston Subdivision, two new bridges to carry the CPR North Toronto Subdivision over the depressed CN Weston Subdivision, and construction of retaining walls. The retaining walls for the depressed corridor are approximately one kilometer long with a maximum excavation depth of 11 metres.

An interlocking steel pipe retaining wall was installed to permanently retain up to 12 metres of cut along the depressed corridor. This system was selected since it provided a predictable method for dealing with ground water during and after construction. This type of piling system was developed in Japan and was new at the time to the Ontario market (Anderson et al., 2007).

Installation of the steel pipe pile retaining wall was completed in 2010. It was established during installation that a significant number of pipe piles were damaged or potentially damaged. This resulted in a new pile validation contract to extract and replace damaged piles. Based on data gathered from the pile validation work, a scope of work was developed for the tendering and award of a new subcontract for the sealing of P-T interlocks suspected or known to be damaged and leaking.

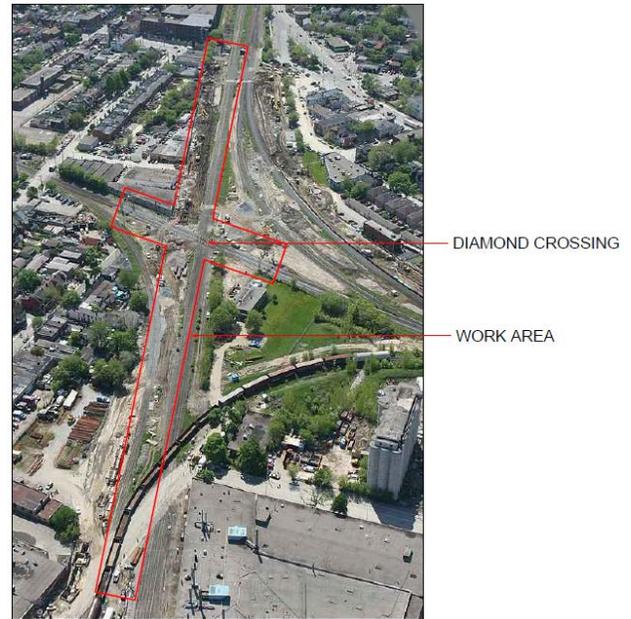


Figure 1. Aerial view of WTD site

## 3 SPECIFIED REQUIREMENTS

The specifications required the design, means and methods and provision of all equipment, materials and labour for jet grout sealing of P-T interlocks which have been determined to be leaking or have the potential to leak as a result of damage during installation under a previous contract. Sealing of P-T interlocks was required to be completed from the soil side of the 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.

## 4 JET GROUTING

Jet grouting is a ground modification system used for the in situ mixing of soils with a stabilizer (typically neat cement grout). This stabilizer is injected at very high pressures ranging from 300 to 600 bars 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. 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. 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 system was used at the WTD project to install a low permeability barrier at 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. Grout is used for eroding and mixing of the soil; the compressed air shroud amplifies the erosive quality of the injected cement grout.

## 5 SUBSURFACE CONDITIONS

The subsurface material present within the project area comprises of fill of thickness ranging from 1 to 3 m, clayey silt to silty clay, sand to sand and silt and clayey silt to silty clay till (Fig. 3). 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 site.

Excavation depths for the depressed corridor will extend to 12 m and into the fill, clayey silt to silty clay, and sand to sand and silt deposits. The sand to sand and silt soils are water bearing and form an aquifer at the site. Approximately 550 lineal metres of the proposed excavation will be below the groundwater table.

The interlocking pipe pile was designed to penetrate below the groundwater level and extend to the underlying cohesive clayey silty to silty clay till to restrict the potential flow of water into the excavation. Sheet pile cut-off walls were also installed perpendicular to the main support walls to form cells where the main excavation penetrates below the baseline groundwater level.

Jet grouting was performed to depths established by the consultant at the selected locations. The location and depths varied across the site based on the profile of the excavation of the depressed corridor.

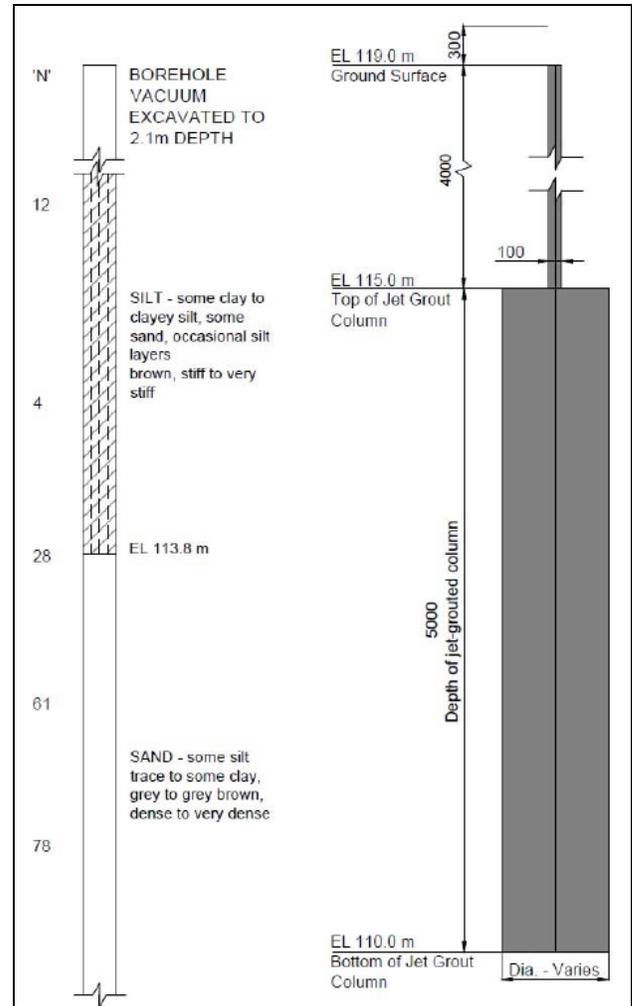


Figure 3. Subsurface profile and test column section

## 6 METHODOLOGY

Jet grout test columns were installed in three phases, totaling fourteen test columns. All fourteen test columns were installed at the East Corridor between pipe piles EW70 to EW109. A layout of the test columns is shown in Figure 4. Phase 1 test columns were installed at the centre of the East Corridor between piles EW70 to EW80. Six columns were installed in Phase 1 to evaluate a wider range of lift rates (i.e. 0.2 to 0.6m per minute). Phase 2 test columns consisted of a set of eight test columns installed adjacent to the East Wall (west side). These columns were offset 0.5 m from the centre of the P-T interlock and installed between piles EW85 and EW109. Test columns were constructed from Elevation 119.0 m and jetted from Elevation 115.0 m to 110.0 m. The permeability testing methodology was modified for Phase 2 test columns. Phase 3 testing was performed on two additional production jet grouted columns.

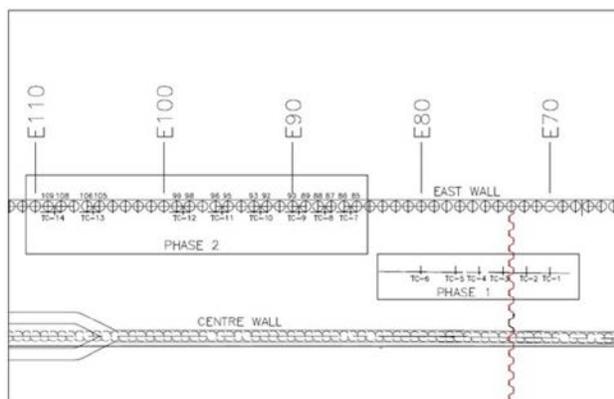


Figure 4. Layout of test columns

### 6.1 Installation of test columns

Each test column location was drilled to 9 metres below ground surface (mbgs) using grout as the flush medium. Drilling of the 100 mm diameter hole was done by using the rotary method with a drag bit attached below the jet-grout monitor.

Grout was introduced into the system at the batch plant approximately 0.5m above the target depth. The pumping mode was changed to “jetting” upon reaching the target drilled depth and the desired injection pressure was selected. The test columns were installed from the bottom upwards, from 9.0 to 4.0 mbgs, then tremie grouted under gravity head only from 4.0 m to ground surface. The lift rate for each column was selected by using the settings on the Casagrande C8 drill rig, in order to maintain a constant lift rate throughout the jetting process.

A single 3 mm nozzle was used to install columns TC1 to TC7 using the double-fluid jet grouting process (i.e. grout surrounded by a jacket of compressed air). Test columns TC8 to TC14 were installed by using a single 4.5mm nozzle.

Batching of the grout was done by weight and the mixes were programmed using the automatic settings on TWM-20 batch plant. The cement (Type 2 equivalent – 75% Portland and 25% slag) was discharged into the mixer from the 33 tonne capacity horizontal silo located above the mixing plant.

A steel conductor pipe was installed coincident with the central axis of each column, after completion of jetting, in Phase 2 such that the pipe extended from surface to 6mbgs. The steel pipe was secured at surface by using steel hangers. These pipes were installed to function like an overburden casing to facilitate in situ permeability testing. No conductor pipes were installed during Phase 1 since the columns were exhumed prior to conducting the in situ permeability testing. PVC conductor pipes were installed prior to backfilling the exhumed Phase 1 test columns. The installation of the conductor casing was improved during Phase 2 based on lessons learned.

during Phase 1. Figure 5 shows the site arrangement at the test area.



Figure 5. Site arrangement at test area

### 6.2 Grout mix design

A 1.2:1 (by weight) water-to-cement ratio grout mix with bentonite (dosed by weight of water) and super-plasticizer (dosed by weight of cement) was selected for the test columns. The bentonite (8% slurry concentration) was pre-hydrated for more than 24 hrs and constantly recirculated. Batching of the bentonite slurry was done by weight. The pre-hydration mixing plant was equipped with two holding tanks and a high shear Hany colloidal mixer. Calibration checks and trial batches were performed prior to the installation of the test columns. The grout mixes utilized and the mixing order of the components are presented in Table 1.0.

Table 1. Grout mixes used for the test program

MIX A	MIX B	MIX C
Water	Water	Water
2% bentonite (by weight of water) – Premium Gel	3% bentonite (by weight of water) – Premium Gel	3.5% bentonite (by weight of water) – Premium Gel
Type 20 cement	Type 20 cement	Type 20 cement
1% Super plasticizer (Rheobuild 1000) – by weight of cement	1.5% Super plasticizer (Rheobuild 1000) – by weight of cement	1.65% Super plasticizer (Rheobuild 1000) – by weight of cement

The drilling rate, thrust pressure, torque, rotation rate, lifting rate, grout pressure, grout flow and injected volume per metre of column were recorded using the Jean Lutz LT3 Automatic Parameter recorder. This unit is installed on the Casagrande C8 drill rig and linked to the controls e.g. automatic lift settings, etc.

### 6.3 Quality control

The following quality control measures were implemented during the grouting program:

**Specific gravity** – Prior to injection, the specific gravity of the grout was measured in accordance with the method described in API Recommended Practice 13B-1. This test was used to verify the water/cement (W/C) ratio of the grout. The specific gravity of the spoils (soil-cement) generated from the jetting process was also measured.

**Apparent viscosity** - The Marsh time of the grout was measured in accordance with the method described in API Recommended Practice 13B-1 with a Marsh funnel and a calibrated container. The apparent viscosity of the grout was measured to ensure adequate dosage of superplasticizer.

**Bleed** - The bleed capacity of the grout was measured in accordance with the method outlined under ASTM C940 using a 250 mL graduated cylinder.

Samples of the grout and spoils from jetting were captured and cast in cube moulds for unconfined compression strength (UCS) testing. Samples of spoils from jetting were captured and cast in cylinders and sent to the lab for permeability testing.

### 6.4 Exhumation of test columns

The sizes of the columns installed during Phase 1 were verified by exhuming the upper 0.3 m section of each column. Jet grout parameters used for the installation of Phase 1 columns resulted in diameters ranging from 0.8 m to 1.8 m.

### 6.5 Jet grout parameters

A wide variation of jet grout parameters were used during Phase 1 test column installation. During installation of Phase 2 columns, parameters that initially resulted in 0.8 and 1.2 m diameter columns were used. However, during testing and variation in permeability results, jet grout parameters that resulted in 1.2 m diameter column were eventually selected. Table 2.0 provides a list of the jet grout parameters that were used for the test program.

Table 2. Jet grout parameters used for the test program

Col. ID	Pressure (bar)	Flow rate (L/min)	Jetting (RPM)	Lifting rate (m/min)	Nozzle Dia. (mm)	Col.dia. (m)	Grout mix
TC1	320	95	20	0.3	3	1.2	A
TC2	320	95	20	0.4	3	NM	A
TC3	Abandoned test column						
TC4	320	95	20	0.5	3	0.8	A
TC5	320	95	20	0.6	3	NM	A
TC6	320	95	20	0.2	3	1.8	A
TC7	320	95	20	0.5	3	NM	A
TC8	320	155	20	0.6	4	NM	A
TC9	320	155	20	0.5	4	NM	A
TC10	320	155	20	0.5	4	NM	A
TC11	320	155	20	0.4	4	NM	A
TC12	320	155	20	0.4	4	1.2	B
TC13	320	155	20	0.4	4	NM	B
TC14	320	155	20	0.4	4	NM	C

NM – Not measured

## 7 PERMEABILITY TESTING

The permeability testing proposed by the contractor was in general conformance with the ASCE Jet Grouting Guideline (2010). Testing of Phase 1 columns was done using the proposed methodology, which is also considered as standard industry practice. The testing procedure was modified for Phase 2 columns.

### 7.1 Phase 1 Testing

Two of the test columns TC 1 and TC 4 were cored using a HQ coring assembly in an attempt to ensure that the post-installation drilling process did not damage the test column to an extent that would preclude in situ permeability testing. Coring of the test columns was performed six days after installation. The jet-grouted columns were cored from 4 to 8 mbgs (EL. 115.5 to 111.5), leaving the bottom 1 m of the column intact. A sleeve pipe was installed above test columns TC 1 and TC 4, after the diameter was verified by open cut-excavation. The sleeve pipes were offset from the centre of columns TC-1 and TC-4 by 0.3 m and 0.15 m respectively.

In situ permeability testing of the soil-grout columns was performed by using an inflatable borehole packer, magnetic flow meter, pressure gauge and the pump on a colloidal grout plant for water supply. The desired gauge pressure was achieved by regulating the water supply before the flow meter by using a 3-way valve and recirculating water to the holding tank at the grout plant. Testing was performed over a 10-minute period by

maintaining a constant gauge pressure. Flow rates and the cumulative volume were recorded during each test. Calibrations checks were performed on the pressure gauge and flow meter prior to conducting the tests.

A falling head test was performed on column TC4 to verify the results by eliminating the pressure gauge and flow meter. The test was done by inflating the borehole packer and elevating the water supply hose to achieve the target water pressure at the top of the column.

## 7.2 Phase 2 Testing

A 50mm diameter hole was drilled at the centre of the conductor pipe to a target depth of 7mbgs. This resulted in a 1m test section of the soil-grout mass for in situ permeability testing. The drilling of the 50mm diameter hole was done by using a bicone drill bit and rotary drilling technique. Water was used as the flushing medium to advance the hole to the target depth. Drilling of test holes was performed approximately one week after the columns were installed. Each test hole was flushed clean upon completion of drilling.

A borehole pressure transducer (Level Troll 500) was lowered to approximately 100mm off the test bottom of the drilled hole and the cable was secured to the riser pipe. The water level trend in the drilled hole was measured for half a day to confirm that static equilibrium condition has been reached. After confirming that static water level has been achieved, a slug test was conducted.

The Level Troll was reset for a new test to record the water level change in logarithmic time. A slug of fresh water was then quickly introduced into the hole, allowing the water level to rise quickly above the static level. Monitoring of the water level in the drilled hole was conducted until 67% of the recovery was achieved. After completion of each test, the data were downloaded and analyzed using Hvorslev's method.

Based on the permeability testing, results obtained for column TC-12 were considered the most favorable for production work. A full-depth core was performed at 0.3 m from the centre of TC-12 using the HQ-3 system. A down hole recorded visual survey of the full depth cored hole

was done to verify the consistency of the jet grout column. Additionally, TC-12 was exhumed for visual inspection of the jet grout/P-T interlock interface. Both the video inspection and the exhumation provided valuable information and confirmed a uniform consistency without any indication of voids. The seal created at the P-T interlock was also confirmed to be watertight. Figure 6 shows the test arrangement for Phases 1 and 2.

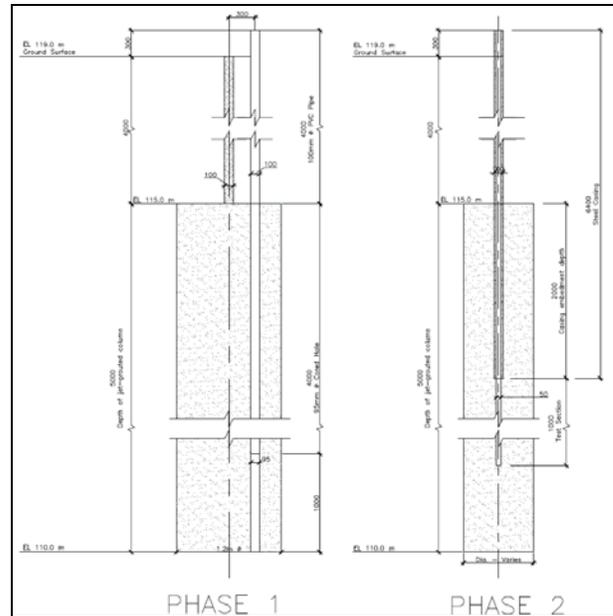


Figure 6. Test column arrangement for Phases 1 & 2

## 7.3 Phase 3 - Proof Testing

Proof testing was performed on two production jet grout columns. A steel conductor pipe was installed coincident with the central axis of the freshly installed column. This pipe was installed to function as an overburden casing to conduct the 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 the drilling of a test hole in the relatively weak soil-grout matrix. After setting the conductor pipe in place, an inner 28 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 for approximately 20 hours. The test hole was successfully developed with a significant amount of care and monitoring to establish a suitable time for the removal of the inner piper

After achieving static conditions, a slug test was performed and all test data was captured using the Level Troll downhole pressure transducer. The data obtained from the test were analyzed using Hvorslev's method. The layout and arrangement for Phase 3 testing is shown in Figures 7 & 8.

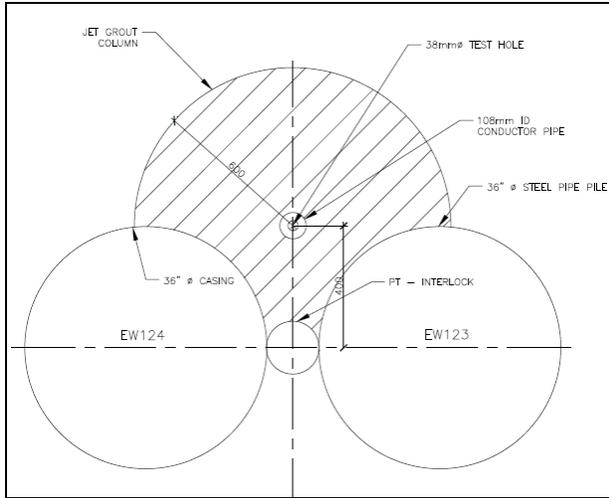


Figure 7. Layout of Phase 3 jet grout test column

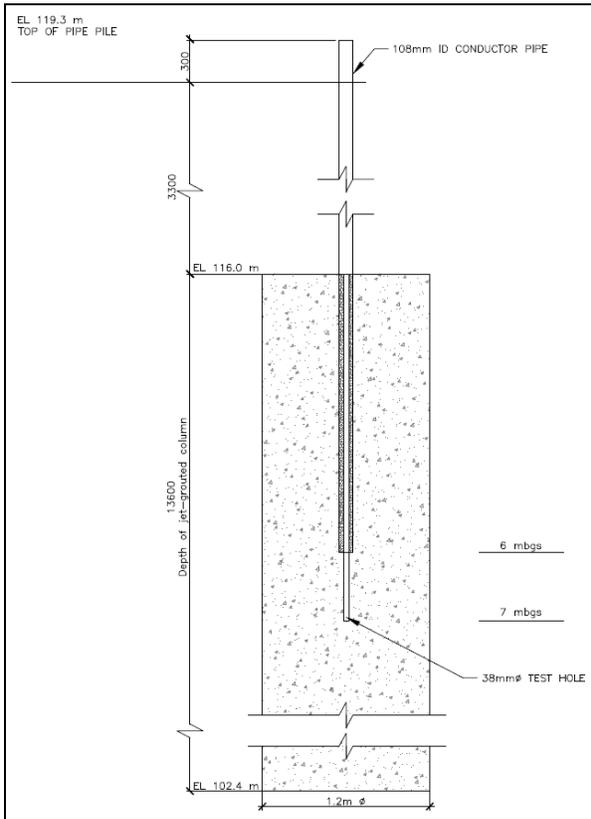


Figure 8. Phase 3 test arrangement

## 8 RESULTS

A summary of the permeability results obtained from the test program is provided in Table 3.0.

Table 3. Summary of permeability test results

Col. ID	Permeability (cm/s)		Remarks
	In situ testing	Lab Testing	
Pre-Production Testing			
TC1	$2.6 \times 10^{-4}$	NM	Constant head test
TC2	NM	NM	
TC3	$2.5 \times 10^{-5}$	NM	Falling head test
TC4	NM	NM	
TC5	NM	NM	
TC6	NM	NM	
TC7	NM	NM	
TC8	$1 \times 10^{-5}$	NM	Slug test
TC9	NM	NM	Abandoned column
TC10	$4 \times 10^{-5}$	NM	Slug test
TC11	$2.6 \times 10^{-5}$	$2.8 \times 10^{-6}$	Slug test
TC12	$7 \times 10^{-6}$	$1.9 \times 10^{-5}$	Slug test
TC13	$6.1 \times 10^{-5}$	$3.2 \times 10^{-8}$	Slug test
TC14	$3.2 \times 10^{-4}$	$1.3 \times 10^{-6}$	Slug test
Proof testing			
PTC-1	$3.8 \times 10^{-7}$	$2.6 \times 10^{-8}$	Slug test
PTC-2	$2.9 \times 10^{-6}$	$1.7 \times 10^{-7}$	Slug test

## 9 DISCUSSION

Permeability test results can be greatly affected by the core drilling process and the quality of the borehole. The coring process could have induced fractures within the soil-cement column due to the action of the flush during boring. The packer must be properly sealed to prevent any leaks and works best when the wall of the borehole is smooth and completely intact. A small increase in the amount of water injected during the permeability test – whether this water actually diffuses through the soil-cement mass or not - can easily result in a significant difference in the test results.

The in situ permeability of the soil-grout columns for Phase 1 was calculated by using the following formula:

$$k = \frac{Q}{2\pi HL} \log_e \frac{L}{r} \quad [1]$$

where:

k is the permeability  
 Q is the rate of injection  
 H is the pressure head of water in the test section  
 L is the length of the test section  
 r is the radius of the borehole

The formula provides only approximate values of k and does not account for any flow of water from the test section back to the borehole. Values obtained from the formula are considered to be of the correct magnitude and suitable for practical purposes.

A thorough review of Phase 1 permeability testing methodology was conducted and a revised installation

and testing procedure was proposed. An improved testing methodology to evaluate the in situ permeability of the soil-grout column was used.

Data obtained from the borehole pressure transducer for Phase 2 permeability testing was transferred to a computer and analyzed by using Hvorslev's method (Hvorslev, 1951).

It was essential to gather as much information throughout the installation and testing of the jet grout columns. The testing approach was modified based on the conditions encountered at the site and lessons learned as the installation and testing progressed. A significant amount of data was acquired from the test program to establish conformance with the specified permeability. Figure 9 shows the typical layout of production jet grout columns.

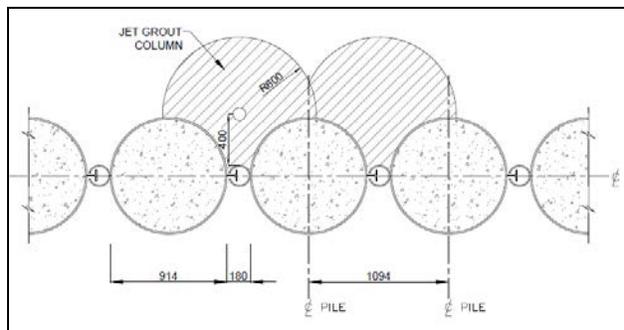


Figure 9. Typical layout of production jet grout columns

## 10 CONCLUSIONS

An extensive test program was successfully completed to verify the in situ permeability and geometric properties of jet grouted columns at the WTD site. A total of three test columns were initially proposed to verify column geometry and in situ permeability. However, fourteen test columns were installed mainly to establish the optimal in situ permeability. The testing methodology was improved for Phase 2 columns (i.e. TC-7 to TC-14) to measure the in situ permeability of the test columns. A wide range of lift rates and variation in grout mix designs were utilized for installation of the test columns.

The most favorable in situ permeability was obtained by jet grouting using a single 4.5 mm diameter nozzle with a lift rate of 0.4m/min and grout mix B (3% bentonite content, dosed by weight of water). Production jet grouting at the site was completed using similar jetting parameters and grout mix design as were used for TC-12.

The modified installation procedure adopted for installation of the test hole on the production columns eliminated the risks associated with drilling and damage to the soil/grout matrix.

## ACKNOWLEDGEMENTS

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## REFERENCES

- Archibald, B, Anderson, V, Crabb, J. and Werner, J. 2007. West Toronto Diamond. Bridges: Economic and Social Linkages Session, 2007 Annual Conference of the Transportation Association of Canada, Saskatoon, Saskatchewan.
- Geotechnical Baseline Report. 2008. West Toronto Diamond Rail to Rail Grade Separation, City of Toronto, Ontario. Prepared by Golder Associates Ltd.
- Hvorslev, J.M., 1951. Time lag and soil permeability in ground water observations. U.S. Corps of Engineer, Waterways Express Station, Vicksburg, Mississippi.
- Moseley, M.P., and Kirsch, K., 2004. Ground Improvement. Taylor and Francis Group.