© 2012 Geo-Foundations Contractors Inc.
(www.geo-foundations.com)

4th International Conference on Grouting and Deep Mixing

Intake Shaft Grout Curtain for the Niagara Tunnel Project

Naresh Gurpersaud[1], Marcelo Chuaqui[2], Daniel Lees[1], Wing Lam[2] and Frank Hu[1]

[1]*Geo-Foundations Contractors Inc., Acton, ON, L7J 1W9, Canada;*
ngurpersaud@geo-foundations.com; drlees@geo-foundations.com; frankhu@geo-foundations.com
[2]*GeoSupport Inc., Mississauga, ON, L5L 5M5, Canada;*
marcelo.chuaqui@geo-support.ca; wing.lam@geo-support.ca

ABSTRACT: A 10.2 km long x 14.4 m diameter tunnel is currently under construction to channel water from the Niagara River to Sir Adam Beck generating station, Niagara Falls, Ontario, Canada. The tunnel's intake structure was excavated and constructed under dry conditions after a comprehensive bedrock fissure grouting program was executed. The grout curtain was specified by the owner's representative, designed by GeoSupport Inc. and constructed in 2007 by Geo-Foundations Contractors Inc. The details of the design, construction and performance of the grout curtain are discussed in this paper.

Regular cement based grouts were used with a variable-dosage cocktail of specialty grout additives to combat the wide variety of rock and groundwater conditions encountered. Grouting of the bedrock was staged from the top of cofferdam cells, caisson wall and rock fill, with the treatment zone between 10m to 55m below normal water level. An automated batching system and real time monitoring system facilitated the injection of over 541 tonnes of cement (dry weight of cement) during 7 months of grout curtain construction. A total of 12,500 m^2 of grouted vertical bedrock face was exposed after completion of excavation. The grout curtain succeeded in achieving the contractually mandated performance threshold of maximum 50 L/s seepage through the entire exposed face.

1.0 INTRODUCTION

The demand for clean, renewable electricity in Ontario, Canada has resulted in the creation of the Niagara Tunnel Project. This project is currently under construction by using the world's largest hard rock tunnel boring machine (TBM) at 14.4 metres in diameter to advance a water conveyance tunnel under the City of Niagara Falls, Ontario, Canada. The total length of the tunnel will be 10.2 km, connecting Sir Adam Beck Generating Complex to the upper Niagara River (i.e. upstream of Niagara Falls) and is expected to be operational in 2013.

The intake shaft excavation for the new tunnel is 16 m x 26 m in plan x 45 m deep. A multiple cell cofferdam seated on bedrock was constructed in the Niagara River by using steel sheet piling and rock fill to facilitate construction of the intake structure. The grout curtain was constructed by Geo-Foundations Contractors within the bedrock to seal fissures comprising of cracks, open horizontal bedding planes and plunging joint networks. The main objective of the grout curtain was to reduce the permeability into the excavation to a controllable rate of less than 50 L/s, as specified in the Geotechnical Baseline Report (GBR). The grout curtain was tied into several other water retaining structures including: the tremie pour at the bottom of the cofferdam; the International Niagara Control Works (INCW) structure; a caisson wall and the INCW bridge piers. Grouting of the bedrock was staged from top of the cofferdam cells, caisson wall and rock fill between the INCW piers, with the treatment zone in the bedrock (i.e. 10 m to 55 m below normal water level). Grouting was completed prior to any attempts to dewater inside the cofferdam.

The bedrock intercepted by the intake structure excavation consists of limestone of the Lockport (middle Silurian), Goat Island and Decew formations, with regular horizontal bedding planes and intermittent, large-aperture, near vertical fracture planes. The grout curtain was 340 m in length and extended to a depth of 51.5 m from the top of rock. The installation of this grout curtain utilized the best modern grouting practices, using stable cement/bentonite grout mixes with additives, together with electronic monitoring equipment for real-time control of pressures, flows and volumes, in order to optimize grout takes and migration. The grout curtain's sternest test is in the interim between completion of the shaft excavation and the TBM's eventual breakthrough. The single line grout curtain has been resisting 45 metres of hydrostatic head across its relatively thin width.

Grouting of the fissured bedrock included full depth fourth-order split spaced holes and employed simultaneous grout injection at multiple holes. A sophisticated suite of drilling and grouting equipment was used, including water-hammer drilling, real-time response-driven additive dosing to modify grout formulations during grout injection and an automated bulk grout batching plant capable of delivering more than 20 m^3 of cement grout per hour. In total, the grout curtain construction required more than 13,000 lineal metres of drilling and consumed more than 541 tonnes of cement. Several verification holes were drilled and two holes were core sampled and tested for residual hydraulic conductivity as part of grout curtain quality assurance program.

Present estimates foresee the grout curtain and cofferdam being in service in excess of 5 years. The grout curtain has continued to perform through the drill and blast excavation of the intake shaft and numerous freeze-thaw cycles of Canadian winter to date.

2.0 BACKGROUND AND PROBLEM STATEMENT

The bedrock within the treatment zone consists of thin to thick bedded dolostone which contains open joint, fissures and bedding planes at two specific horizons where high flows were expected and diffuse type of permeability in other areas. The grout curtain was designed to extend into the top 3m of the low permeability Rochester shale formation in order to alleviate seepage of groundwater below the grout curtain. The formation thicknesses are, from upper to lower: Guelph dolostone (2-3 m); Lockport dolostone comprising of Ermosa, Goat Island and Gasport members (43-45 m); Decew dolostone (2-3m) and Rochester shale (17-19 m).The type of permeability observed at the location of the grout curtain is termed "triple porosity" based on the three forms of void space configuration though which water can flow i.e. small pores, fractures and fissures, and solutioned/karstified joints and beds (KCF, 2006). The small pores, fractures and fissures constitue the diffuse flow system. The majority of groundwater flows through the solutioned/karstified geologic features, or pipes. A key parameter of the grout curtain construction entailed sealing off the entire karst pipe network in the Lockport dolostone to achieve a reduction in flow rate though the grout curtain. A target seepage rate of 31.5 L/s was estimated based on the two water bearing zones being completely sealed. No significant seepage was anticipated through the Rochester shale formation.

Grouting of the intake area was specified to reduce the amount of seepage water into the excavation. A total of 3400 tonnes of cementitous material was allowed for all grouting phases to complete the grout curtain. It was anticipated that following injection of 3400 tonnes of cement, the seepage of water into the excavation would be less than 50 L/s. The main challenge for the grout curtain construction as reported by KCF (2006), was designing the target permeability numbers for the grout treatment zone to achieve a reduction in seepage rate to 50 L/s or less into the intake Tunnel structure during its dewatering to 140 m MSL. The location of the grout curtain is shown in Figure 1.

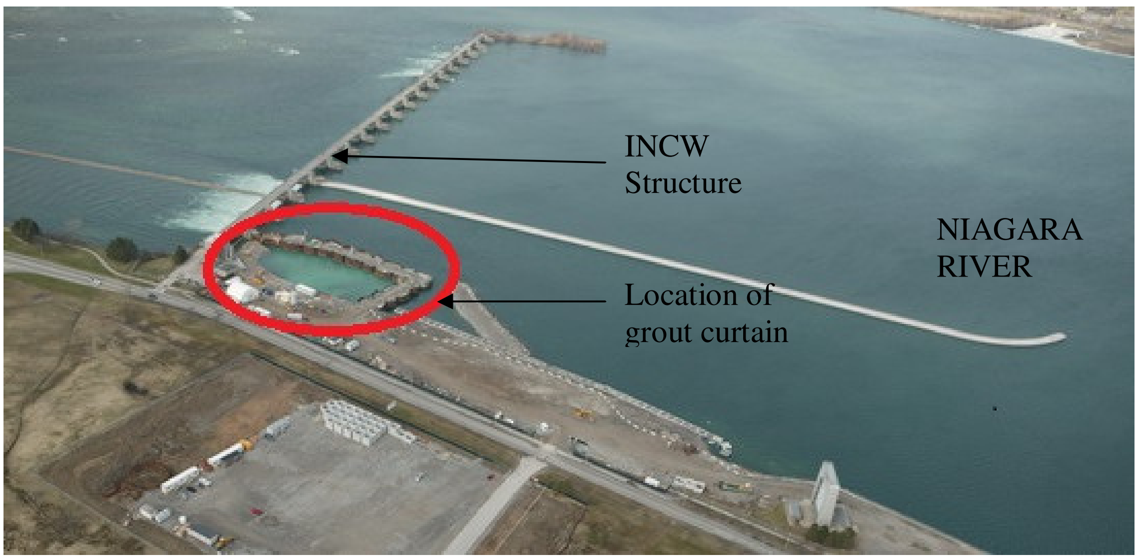

FIG. 1. Location of intake structure

3.0 METHODOLOGY

3.1 Drilling

Grout holes were drilled by using a rotary percussive drilling technique with a down the hole water hammer. The drilling system was carefully chosen to avoid the use of air as a drilling/flushing medium, since air can artificially reduce permeability by plugging open fissures with drill cuttings. The use of air as a drilling/flushing system was only used to install casings within the caisson wall and cofferdam cells to act as a conductor pipe to the top of rock. All drilling for the grout curtain was done with the Wassara Water Hammer system and grout holes were 95mm in diameter. The layout of the grout curtain and the spacing of the grout holes are illustrated in Figures 2 and 3 respectively.

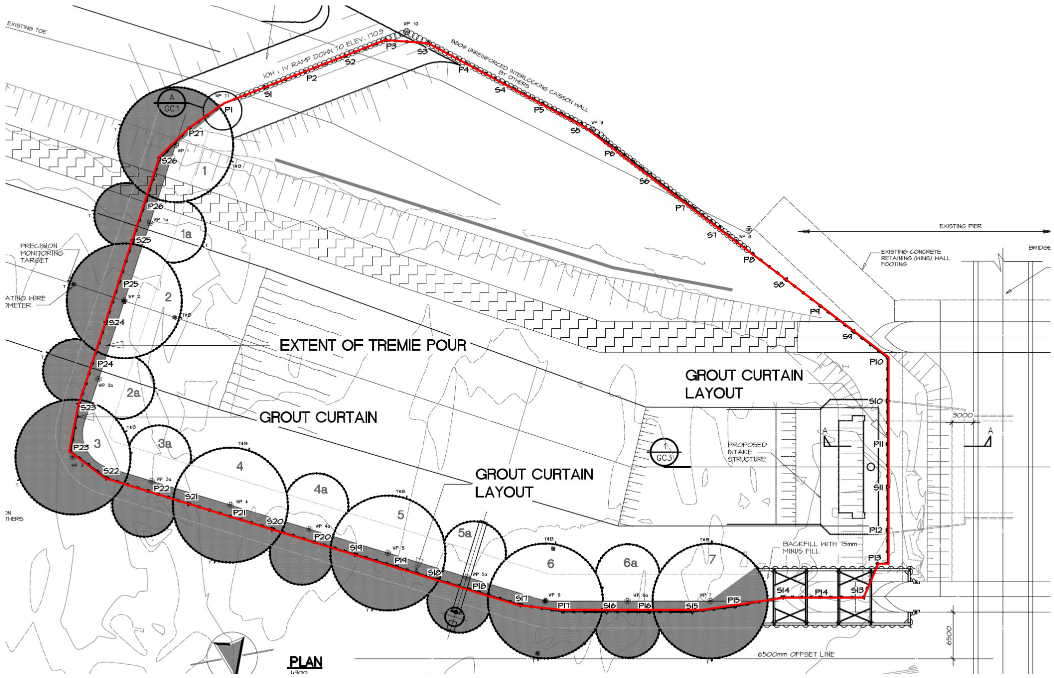

FIG. 2. Layout of grout curtain

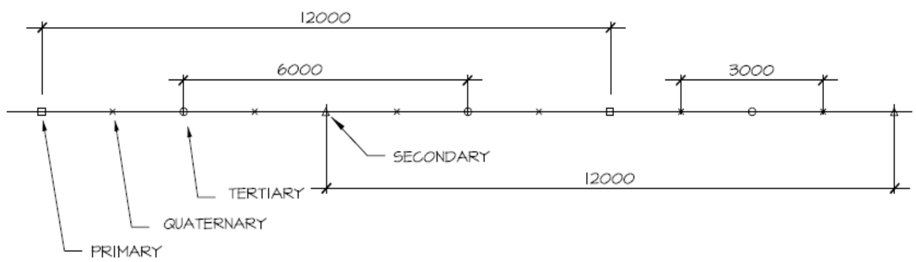

FIG. 3. Spacing of grout holes

3.2 Grouting

The grouting was performed by using the 'stage-up grouting method', where the grout holes were drilled to the target depth before grouting. Grouting was performed by starting from the lowest zone (i.e. 3 m grout zones) and working upwards by using a single inflatable packer.

3.2.1 Grout mix design

A pre-production grout mix testing program was performed to develop the base formulations for the grout curtain. A three phase process is recommended by Chuaqui and Bruce (2003) for the development of high mobility grout on any particular project. The first phase includes a series of formulations developed during a laboratory test program based on site specific conditions. Mix designs are then replicated on site to investigate changes in properties due to differences in materials, mixing equipment or differences in procedures between laboratory and production grouting. The third phase involves verification at regular intervals during production grouting to ensure that grouts are being batched correctly. The main objective of the test program was to establish a base formulation with the following properties:

- Stable (i.e. less than 5% bleed)
- Water/cement ratio between 0.75 and 1.2 (by weight)
- Relatively fluid (i.e. apparent viscosity between 34 and 38 seconds as measured with a Marsh Funnel)

After the base formulation was developed, the second key objective was to develop variations of the base mixes by increasing the viscosity. Two options were proposed for thicker grout mixes as follows:

- Using Rheomac UW-450 to increase the viscosity and improve the anti-washout characteristics.
- Increasing the bentonite content and reducing the superplasticizer content

Several rock grouting projects have demonstrated that the best quality grout curtain is achieved by maximizing the cement content of the grout mix design without compromising the important rheological characteristics such as viscosity, cohesion and stability (Lombardi, 2003). A total of three stable, balanced base grout mixes were used for the grouting program. These mixes were developed based on the geotechnical baseline report (GBR) and a comprehensive review of the hydro-geological features. A pre-construction mix test program was implemented to verify the base mixes. A summary of the grout mixes used for the grout curtain construction is presented in Table 1.

Table 1. Summary of grout mixes utilized for the construction of the grout curtain

Mix 1	Mix 2	Mix 3
Water/cement ratio = 1	Water/cement ratio = 1	Water/cement ratio = 1
Bentonite = 1.6% (BWOW)	Bentonite = 1.6% (BWOW)	Bentonite = 2% (BWOW)
PS 1466 = 1.4% (BWOC)	PS 1466 = 1% (BWOC)	PS 1466 = 1% (BWOC)
Marsh time = 38 sec	Marsh time = 45 sec	Marsh time = 75 sec

Notes: 1) Rheomac UW-450 was added to Mix 3 as required at 0.5% (BWOC)
2) BWOW – By weight of water
3) BWOC – By weight of cement

Bentonite was prehydrated for a mimimum of 12 hours and stored in tanks that were outfitted for continuous recirculation. The bentonite slurry was formed at 7% (i.e. by weight of water) and proportioned with water in the mixer prior to the addition of cement to achieve the correct slurry concentration for the selected mix.

3.2.2 Grouting refusal criteria

The refusal criteria for grouting of each zone (i.e. 3m) comprised of the following:

1) Minimum flow at a maximum pressure

The minimum effective pressure was 1 PSI per foot of depth with a refusal flow rate of 2 L/min

2) Maximum volume

The maximum volume criterion was established based upon the results of the mix design program and the in-situ permeability testing. A maximum volume of 10,000 L was used as the grouting cut-off.

The grout mix was changed from the initial mix (i.e. Mix 1, refer to Table 1) based on cumulative volume injected, trends in flow and pressure reduction. An injected grout volume of 2000L per 3 m zone was used as the basis for a change in mix type, unless a gradual reduction in the flow rates and grouting pressure were observed.

3.2.3 Grouting Equipment

Grout was batched by using an automated grout plant to ensure accurate proportioning of the mix. The automated batching system was capable of producing 20 cubic metres of grout per hour. Multiple hole grouting was performed with up to six holes being grouted simultaneously. A general arrangement of the project site showing the layout of the equipment is illustrated under Figure 4. Grout was transferred from the mixing plant to the agitator in the grout plant and then distributed using Moyno pumps to supply flow control bins (FCB) for further distribution to each grout hole. Each flow control bin was outfitted with a return line to the agitator tank. The flow control bins consisted of a grout header with three feed lines. At the header, each feed line was fitted with monitoring equipment consisting of a magnetic flowmeter, pressure transducer and anti-washout dosage pump with each line being equipped with a control valve. Each feed line transferred the grout to an electric hose reel outfitted with 25mm diameter grout hose (i.e. hydraulic hose) and a single inflatable packer for injection into the hole.

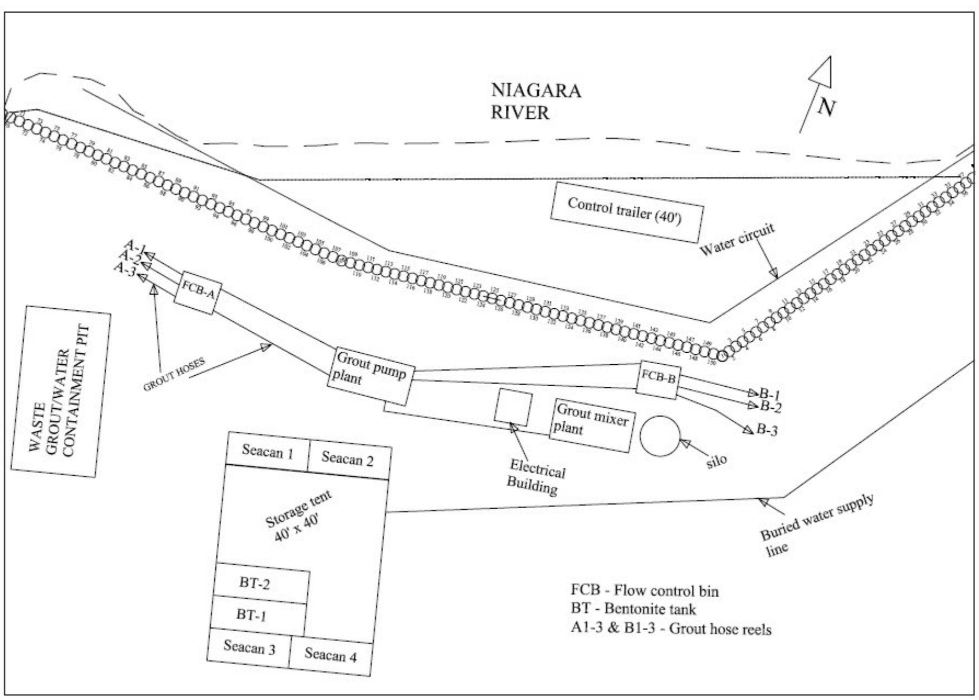

FIG. 4. General arrangement of grouting equipment

Packers were sized to fit the drill hole and inflated with nitrogen. Water-testing was carried out using a double inflatable packer isolating 3.0 metre zones and a single packer was used for most quaternary holes. All grouting was performed by using single inflatable packers.

3.3 Quality assurance and quality control

Quality assurance and quality control are key aspects for the implementation of an effective grouting program. The completeness and quality of a grouting program requires careful and accurate monitoring of the work at all times and modifications as dictated by the observed grout behavior during injection (Warner, 2004).

3.3.1 Quality assurance (QA) program

The ground condition was assessed based on records obtained for each production drill and grout holes. This was achieved by Monitoring While Drilling (MWD) and Monitoring While Grouting (MWG). The information gathered was essential for the successful and efficient execution of the work. The quality assurance (QA) program was designed to achieve the following objectives:

- Provide data to verify the accuracy of the pre-construction assumptions;
- Provide data to allow for verification and adjustments of the design;
- Provide data to demonstrate incremental improvement of the ground conditions (i.e. grout take reduction ratios and improved ground conditions during drilling).

The QA program included the collection and review of data from the drilling operation, water pressure testing and the grouting operation. Drill logs were completed for every hole drilled and water testing was performed on all holes to provide permeability data for the various zones. This information was used to plan the grouting work and adjust mix designs as required. Zones of similar permeability were grouted at the same time. The grouting and water testing data were analyzed to verify a reduction in permeability between different orders of holes for similar horizons.

Real time monitoring of the grouting program allowed for adjustments to be made during grouting of each hole. The data was logged and analyzed to determine which areas required additional treatment (i.e. placement of tertiary and quaternary holes).

The information from each individual grout line was transmitted back to the data logger, recorded and displayed on a real-time basis. Flow, pressure and cumulative volume versus time were displayed for each grout line. All information recorded was kept in electronic and hard copy format on a daily basis.

3.3.2 Quality control (QC) program

The quality control program was designed to ensure that the work was executed as planned. The quality control measures implemented during the drilling operation included verification of the hole depths and inclinations. Each drill hole was sounded with a tape to confirm the accuracy of the depth shown on the drill logs. The hole alignment was checked on 2% of the drilled holes by using a down hole Boretrack system.

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

1) Specific gravity - The specific gravity of the grout was measured in accordance with the method described in API Recommended Practice 13B-1 with a Baroid Mud Balance. This test was used to verify the water/cement (W/C) ratio of the grout.
2) 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 the superplasticizer.
3) Bleed - The bleed capacity of the grout was measured in accordance with the method outlined under ASTM C940 using a 250 ml graduated cylinder.
4) Pressure filtration coefficient - The pressure coefficient was measured by using an API filter press.

The frequency of the quality control checks increased during changes in the grout mix.

4.0 RESULTS

The grout curtain was successfully completed in July, 2007 after 7 months of construction. A total of 212 grout holes were installed for the single line grout curtain using a primary, secondary, tertiary and quaternary (P,S,T,Q) sequence. All quaternary holes were installed although the results indicated a significant reduction in permeability after the tertiary holes were grouted. Water testing was performed on all grout holes to provide permeability data for the various zones. The water testing results were used to plan the grouting operations, where zones of similar permeability were grouted at the same time.

Grouting was done using the stage-up method as previously described, where up to six holes were grouted simultaneously. The water testing results indicated two zones with high permeability, similar to results presented in the GBR. The highly permeable zones were encountered in the upper Lockport formation (Ermosa) and the lower Lockport (Gasport) formation. The primary series of grout holes provided meaningful data to structure the grouting program to target specific zones. A significant reduction in grout quantity was observed between the primary and the secondary stage, indicating the effectiveness in targeting the high flow areas. Figure 5 shows the reduction in average grout volume for P, S, T, Q and verification grout holes.

A total of 22 verification holes were also drilled after completion of the quaternary holes. The verification holes were installed along the path of the grout curtain, especially in areas with considerable grout takes. A flow analysis was done using data obtained from the verification holes and resulted in a seepage rate of 45 L/s. The seepage rate obtained was close to the recommended value as proposed by KCF Groundwater Inc. in a pre-construction hydrogeology report. The post-construction verification program also included two cored holes to the full depth of the grout curtain. Grout was observed on the core samples at the depths corresponding to the highly permeable zones. Figure 6 shows partial excavation for the intake structure.

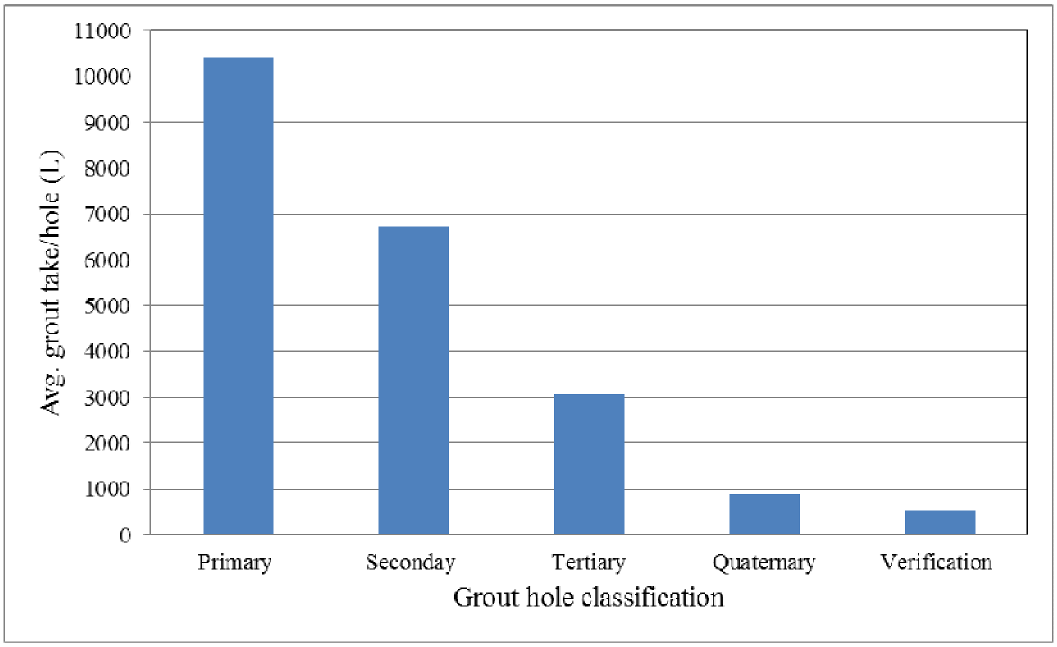

FIG. 5. Average grout volume per hole

FIG. 6. Intake structure excavation

5.0 CONCLUSIONS

The grout curtain for the Niagara Tunnel Facility Project was successfully completed after 7 months of construction, satisfying the seepage requirement of less than 50L/s. The cement consumed to achieve the target permeability value was 541 tonnes, which resulted in a difference of 2,859 tonnes from the specified quantity. The low grout takes were a result of the selection of the grout mixes, continuous review of data and real time monitoring during grouting. A single line grout curtain was installed with up to fourth order split-spaced grout holes and each grout hole was water-tested to obtain permeability data.

Grouting was done throughout the winter without any impacts on the quality of the work. The grout curtain is expected to be in service until 2013 with remarkable performance to date. The most current data acquisition system, drilling and grouting equipment and a well implemented QA/QC program were utilized to successfully complete this project.

REFERENCES

Chuaqui, M.H. and Bruce, D.A., (2003). "Mix design and quality control procedures for high mobility cement based grouts," *Proceedings of the ASCE Specialty Conference in Grouting in Geotechnical Engineering*, New Orleans, LA, pp. 1153-1168.

KCF Groundwater Inc., (2006). "Target permeability calculations – intake structure bedrock grouting," *Report on hydrogeologic setting prepared for GeoSupport.*

Lombardi, G., (1985). "The Role of Cohesion in Cement Grouting of Rock," *15th ICOLD Congress*. Lausanne, Switzerland, Q58, p.13.

Niagara Tunnel Project, (2005). *"Geotechnical Baseline Report,"* Appendix 5.4, pp. 19-63.

Warner, J, (2004). *"Practical handbook of grouting – Soil, rock and structures."* John Wiley and Sons Inc., New Jersey.