An appropriate method for constructing deep foundations that must penetrate artesian aquifers

Jim Bruce, Naresh Gurpersaud, Zhong Han, Mark Montgomery & Hiu Lee
Keller Foundations Ltd., Acton, ON, Canada

ABSTRACT

Deep foundations embedded in artesian aquifers can be the cause of serious problems during, and more importantly, after their installation, due to a disproportionately high risk of washout during construction in the case of drilled shafts, or post-construction soil loss in the case of driven displacement and helical piles inadvertently acting as wicks, which can in turn lead to settlement due to upward migration and eventual loss of eroded soil particles. Both of these problems can be addressed using a unique method described herein. Properly managed, the use of small diameter drilling methods (i.e. micropiles) can significantly reduce these risks associated with penetration of artesian aquifers. A case study is presented, detailing a recent application of this appropriate approach at an urban transportation infrastructure construction project requiring deep foundations in Richmond Hill, Ontario. Deep foundations, in the form of soil-bonded micropiles, constructed with extra reinforcement in order to be suitably stiff to satisfy the Structural Engineer’s requirements, were advanced into an artesian aquifer locally notorious for causing problems. The artesian aquifer that underlies this site exhibits a head pressure of 2 metres above ground elevation. Keller, operating at the time as Geo-Foundations Contractors, designed and installed high-capacity, soil-bonded micropiles to support the new bridge abutments. Micropiles were successfully embedded in the artesian aquifer, without any negative impacts during or after their construction. Each of the 14 no. micropiles was designed for factored axial compression loading of 1070 kN and factored axial tension loading of 325 kN. Verification pre-production load testing proved maximum grout-to-soil adhesion values of 364 kPa and 421 kPa at the north and south abutments, respectively. A uniquely suitable installation process known as continuous-grout-flush, employing cement grout (specific gravity ≥ 1.85 g/cm^3) as the flushing medium was effective in counteracting the potentiometric artesian head at this site during and after micropile installation. All production piles were advanced to their respective target depths at both abutments without any washout and without any compromise to grout-to-ground bond stress. This paper provides a detailed description of the continuous-grout-flush micropile construction method that is suitably safe and appropriate for installation of deep foundations that require breaching of the confining layer of an artesian aquifer.

RÉSUMÉ

Les fondations profondes enfouies dans les aquifères artésiens peuvent être la cause de sérieux problèmes pendant et surtout après leur installation, en raison d'un risque disproportionné de lessivage pendant la construction dans le cas de puits forés ou de pertes de sol après la construction dans le cas de déplacement piloté et pieux hélicoïdaux agissant par inadvertance comme des mèches, ce qui peut à son tour conduire à un tassement dû à la migration vers le haut et à la perte éventuelle de particules de sol érodées. Ces deux problèmes peuvent être résolus en utilisant une méthode unique décrite ici. Correctement gérée, l'utilisation de méthodes de forage de petit diamètre (c'est-à-dire des micropieux) peut considérablement réduire ces risques associés à la pénétration des aquifères artésiens. Une étude de cas est présentée, détaillant une application récente de cette approche appropriée à un projet de construction d'infrastructures de transport urbain nécessitant des fondations profondes à Richmond Hill, en Ontario. Des fondations profondes, sous la forme de micropieux liés au sol, construits avec un renfort supplémentaire pour être suffisamment rigides pour satisfaire aux exigences de l'ingénieur en structures, ont été avancées dans un aquifère artésien connu pour causer des problèmes. L'aquifère artésien qui sous-tend ce site présente une pression de tête de 2 mètres au-dessus du niveau du sol. Keller, qui travaillait à l'époque sous le nom de Geo-Foundations Contractors, a conçu et installé des micropieux à haute capacité, liés au sol, pour soutenir les nouvelles culées de pont. Les micropieux ont été intégrés avec succès dans l'aquifère artésien, sans aucun impact négatif pendant ou après leur construction. Chacun des 14 non. les micropieux ont été conçus pour une charge de compression axiale pondérée de 1070 kN et une charge de traction axiale pondérée de 325 kN. Les essais de vérification de la pré-production ont révélé des valeurs maximales d'adhérence entre le coulis et le sol de 364 kPa et de 421 kPa respectivement dans les culées nord et sud. Un procédé d'installation unique, connu sous le nom de coulis à coulis continu, utilisant un coulis de ciment (densité ≥ 1,85 g/cm^3) comme agent de rinçage, a été efficace pour contrer la tête artésienne potentiométrique sur ce site pendant et après l'installation des micropieux. Tous les pieux de production ont été avancés à leurs profondeurs cibles respectives dans les deux culées sans aucun lavage et sans aucun compromis sur la contrainte de liaison entre le coulis et le sol. Cet article fournit une description détaillée de la méthode de construction de micropieux à coulis continu et à coulis continu qui est convenablement sûre et appropriée pour l'installation de fondations profondes qui nécessitent la rupture de la couche de confinement d'un aquifère artésien.

1. INTRODUCTION

An aquifer is typically defined as an underground layer of porous and permeable material such as fractured rock, gravel, sand, or silt within which water flows and is stored.

An artesian aquifer is an aquifer confined by an impermeable confining cover and contains groundwater under positive pressure, as illustrated schematically in Figure 1.

The confinement and the positive water pressure causes the water level in a well or borehole that breaches the confining layer to rise to a point where hydrostatic equilibrium is reached. In other words, any breach of the artesian aquifer that connects to atmospheric pressure (be it a well, a borehole or a shaft for deep foundation installation) would induce an upward movement of the underground water and create ideal conditions for erosion and potentially result in instability and ground settlement.

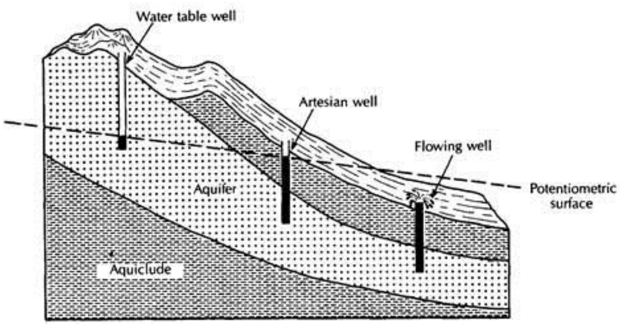

Figure 1. Schematic depiction of an artesian aquifer (Fetter, 2001)

Artesian aquifers manifest themselves in nature as natural springs or spring-fed lakes/ponds, or in rare instances as quicksand.

2. CHALLENGES INHERENT TO CONSTRUCTING DEEP FOUNDATIONS THAT PENETRATE ARTESIAN AQUIFERS

Deep foundations embedded in artesian aquifers can cause serious problems during, and more importantly, after installation. This is due to the disproportionately high risk of soil loss resulting from the foundation elements inadvertently acting as wicks or openings potentially resulting in an upward migration of soil particles carried by groundwater following the newly introduced pressure relief pathway to surface.

For decades now, geotechnical investigations that knowingly breach artesian aquifers have been conducted using elevated platforms and/or drilling under a head of slurry whether by augering under a head of water or by circulation drilling using water or bentonite slurry as the flushing medium. In the worst risk settings, this approach has been popular because it has been regarded as a method suitable for addressing the risks associated with breaching of the confining layer of an artesian aquifer. But these traditional approaches, while well-intentioned, were as often as not, entirely feeble in counteracting all the bad things that can happen when the confining layer of an artesian aquifer is breached.

3. MICROPILE DRILLING

Micropiles have seen significantly increased utilization in Eastern Canada, and in particular the Greater Toronto Area (GTA), since the turn of the current century, for two principal reasons: their ability to be constructed using relatively small equipment (drill rigs smaller and lighter than a compact car), and their ability to penetrate through boulder-rich deposits and as deep as desired into even the hardest, strongest bedrock. Both of these game-changing features are attributable to one unique aspect of the micropile construction process: circulation drilling.

Circulation drilling involves introducing a fluid (most often compressed air or a combination of air and water) into the borehole via pumping of the fluid through a specially sealed flushing head that connects the drill string to the rotation motor, whereafter the fluid travels down the inside of the hollow drill string and is introduced into the borehole at the cutting face, where it immediately turns to travel up-hole, carrying the cuttings up through the annulus between the outside of the drill string and the borehole wall, with the cuttings and circulation fluid exiting the drilling circuit at the surface as spoil. Figure 2 illustrates a typical micropile construction sequence using circulation drilling.

Reverse-circulation drilling works in much the same way, except that the circulation fluid is introduced into the annulus at the collar of the hole and the spoil is evacuated up and out of the hole via the inside of the hollow drill string.

Included in the category of circulation drilling - and often used for micropile construction - is a method known as slurry drilling, where the circulation fluid consists of simply water or brine, or a solution of synthetic polymer, or a colloidal suspension of bentonite or cement powder. Although bentonite in suspension is a popular circulation drilling slurry, this type of drilling is not appropriate for micropile construction, as the bentonite residue left in-hole acts as a bond breaker, significantly reducing the grout-to-ground bond stress that must develop in order for a micropile to perform.

Synthetic polymer solution slurry is a common drilling slurry used in micropile construction because it is highly effective at stabilizing boreholes that pass through coarse-grained deposits that might otherwise cave in on themselves before the micropile reinforcement and tremie grout can be installed. Synthetic polymer slurry works on the basis of its very high surface tension (3x higher than water alone), forming a particularly effective membrane that, combined with the pressure imparted by the head of slurry, stabilizes the hole from caving in on itself. In stark contrast to bentonite slurry, synthetic polymer solution does not foul the borehole wall, as contact with cement grout (introduced later, during micropile grouting) immediately “shocks” the polymer solution, breaking down the polymer chains and turning the solution to water, all of which is displaced up and out of the hole during the grouting process.

A reasonable way to characterize micropiles is, “heavy duty performance, installed with a light touch” or more simply stated: “heavy duty; light touch.” This potent combination is entirely due to circulation drilling. In stark contrast, by comparison, conventional drilling (i.e. large diameter drilling), typically involves making holes by augering or oscillating large diameter casings using a technique which may be regarded simply as “muck-and-dump.” Although polymer slurry is often used in muck-and-dump, it must be noted that polymer slurry used in this application is decidedly not circulation drilling.

Conventional drilling, for this reason, requires a drill rig capable of imparting large torque and large reaction forces for crowd (pushing down) and retrieval of cuttings (mechanically, by lifting the soil-impregnated auger flights up and out of the hole). For this reason, conventional drill rigs, by necessity, are typically very large and energetic to the point where drilling in close proximity to existing foundations is either physically impossible or unacceptably risky to the stability of the existing foundations.

Conversely, micropile drilling methods such as double-head percussive duplex and continuous-grout-flush are particularly appropriate for drilling in close proximity to existing foundations due to their relatively low-energy drilling processes - entirely attributable to their circulation drilling character. For example, in the case of rock drilling, the principal source of energy is a remotely located air-compressor meaning the energy required to drill the hole (actuate the hammer and flush the spoil) is “outsourced” keeping the drilling footprint very small – ideal for restricted access settings.

Mixing cement powder with water forms a colloidal suspension commonly known as cement grout. Cement grout with a specific gravity exceeding 1.25 g/cm^3 is appropriate for use as a drilling slurry. With the help of additives, cement grout with a specific gravity as high as 2.2 g/cm^3 can be used as a drilling slurry. Such heavy slurry is useful for counteracting artesian pressure when breaching the confining layer of an artesian aquifer.

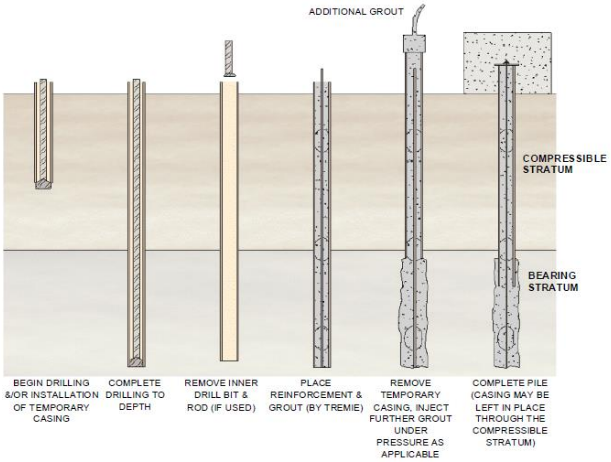

Figure 2. Typical micropile construction sequence using circulation drilling (FHWA, 2000)

This is a special form of slurry drilling known as continuous-grout-flush. It is closely derived from bentonite slurry drilling, but it uses cement powder in colloidal suspension as the drilling fluid that is circulated. Like bentonite, cement in colloidal suspension is effective at stabilizing boreholes due to its heavy unit weight (relative to water) and, like polymer slurry, its ability to form a filter cake on the surface of the borehole wall. Unlike polymer solution slurry, which has a specific gravity very close to that of water, cement grout works particularly effectively as a stabilizer of the borehole due to its high unit weight (s.g. > 1.80) relative to water. It is this attribute that makes continuous grout flush effective at combating washout or post-installation flows at micropiles constructed in artesian conditions: a heavy grout column counters the head pressure of the artesian aquifer, eliminating conditions conducive to flow.

4. CONTINUOUS GROUT-FLUSH TECHNIQUE

Continuous grout-flush using heavy cement grout takes this approach one step further. Like all micropiles, grout-flushed micropiles are replacement-type foundation elements, with the soil being cut and flushed out of the hole, replaced by steel and grout. During the single-visit installation process, drill rods are advanced until penetration to the target depth is achieved – thereinafter the mechanically spliced drill rods stay in the hole to become the micropile reinforcement, with the drill bit sacrificially left in place at the bottom of the micropile. During penetration, grout is introduced continuously into the hole by injection through apertures in the drill bit.

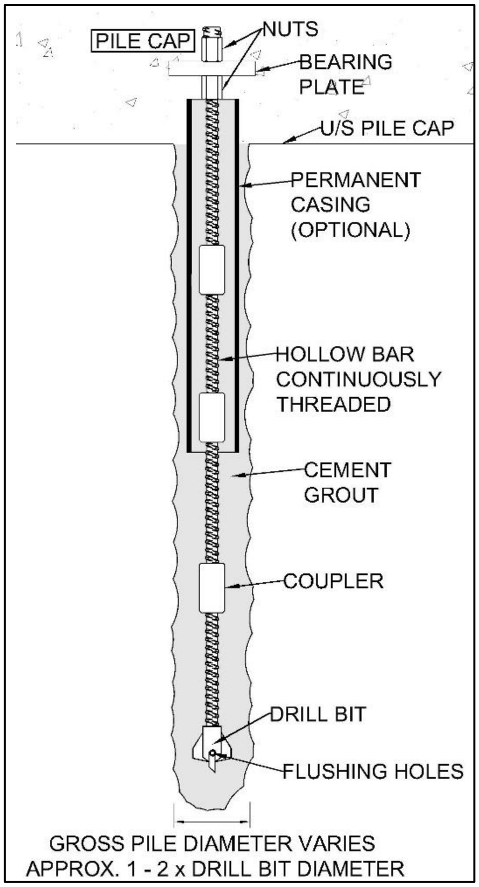

Figure 3. Typical profile of a continuous grout-flush micropile

This continuous grout injection results in excellent grout-to-grout adhesion by two actions, First, the soil that is mechanically cut by the rotating drill bit is flushed out of the hole and instantly replaced by grout, all the while maintaining a fully charged, and thus stable, annulus. Second, as the drill rods are regularly lifted and advanced over the already cut hole depth, the flowing grout promotes erosion of the borehole wall and permeation (to the extent possible) into the remnant soil mass. This secondary action results in varying gross micropile diameter with depth, which amplifies the high unit grout-to-ground adhesion achieved by the first action (Bruce & Gurpersaud, 2009). Figure 3 shows a typical profile of a continuous grout-flushed micropile.

5. APPLICATION OF THIS TECHNIQUE AT RICHMOND HILL GO STATION

5.1 Overview

A single-span pedestrian bridge was constructed at the east side of the existing railway bridge over Major Mackenzie Drive, at Richmond Hill GO Station, Richmond Hill, Ontario, in 2015. An artesian aquifer underlies this site and exhibits a head pressure of 2 metres above ground elevation. According to the structural and geotechnical design of the pedestrian bridge, deep foundations were required and in order to develop sufficient capacity, had to be advanced into the soil layer coincident with the artesian aquifer locally notorious for causing problems.

Keller Foundations Ltd. (Keller), operating at the time as Geo-Foundations Contractors, designed and installed high-capacity, soil-bonded micropiles for the required deep foundations to support the new bridge abutments using continuous grout-flush method. Micropiles were successfully advanced into the artesian aquifer, without any negative effect on pile capacity.

Each micropile was designed for factored axial compression loading of 1070 kN and factored axial tension loading of 325 kN. Two sacrificial pre-production test piles were installed: one at each abutment. Static tension load tests were performed on the sacrificial pre-production piles to a maximum test load of 2000kN, without inducing geotechnical failure.

Maximum grout-to-soil adhesion values of 364 kPa and 421 kPa were achieved at the north and south abutments, respectively during the pre-production load tests. All production micropiles feature permanent steel casing in their uppermost 4m of embedment. All production piles were advanced to the target depth at both abutments without any negative effects resulting from penetration of the artesian aquifer.

5.2 Richmond Hill GO: Sub-surface conditions

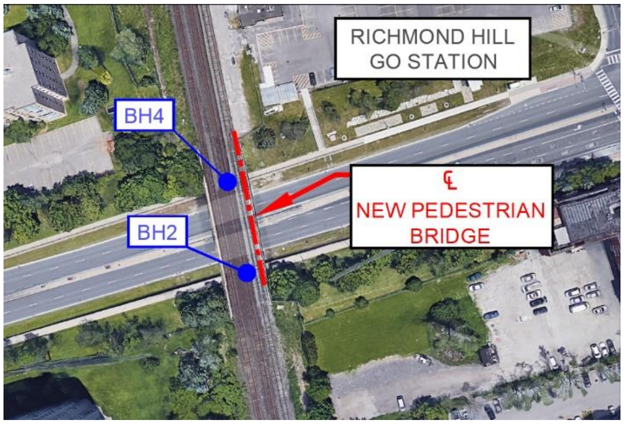

Figure 4. Location of boreholes

A new single-span pedestrian bridge was constructed at the east side of the existing railway bridge over Major Mackenzie Drive (Figure 4). Geotechnical investigation was conducted at two boreholes (i.e. BH4 and BH2) near the north and south abutments of the pedestrian bridge.

The in-situ soil layer information derived from boreholes BH2 and BH4 (SPL, 2015) is summarized below:

Below some fill materials, the native soil in BH2 and BH4 consists of upper silt till to sandy silt till (referred to as Halton Till) overlaying water bearing sand deposits. The upper till extends to an elevation about 214m. The till is in a compact to very dense condition with measured “N” values from the Standard Penetration Tests (SPT) ranging from 26 to 69 blows per 300mm penetration.

The water bearing sand deposits below elevation 214m consist of fine to medium sand. The sand is in a compact to very dense state, with measured “N” values from SPT ranging between 19 to 89 per 300mm penetration.

Therefore, it can be interpreted that the upper silt till to sandy silt till acts as the confining cover and the sand deposits hosts an artesian aquifer.

The north and south abutments were required to be seated on micropiles that were installed into the sandy deposits (i.e. artesian aquifer) to develop the piles’ geotechnical capacity.

For the specific case of the pedestrian bridge, *Keller* designed seven micropiles at the north and south abutment. The arrangement of the micropiles in both abutments is similar. The arrangement beneath the south abutment is shown in Figure 5.

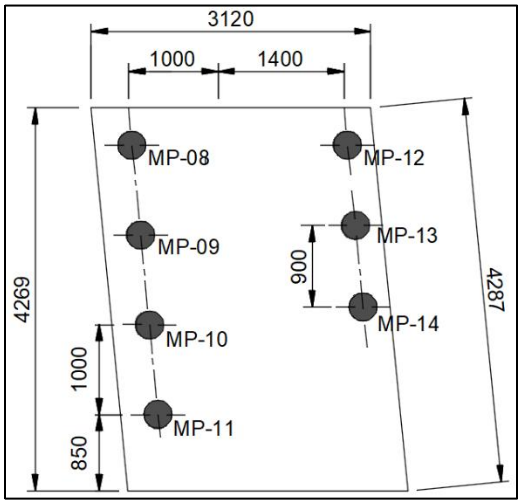

Figure 5. Arrangement of the micropiles along the south abutment

5.3 Richmond Hill GO – micropile installation method

The materials used for the micropiles and their properties are summarized as follows:

1. Micropile central reinforcement is 103/51 (103 mm outer diameter/51 mm inner diameter) hollow bar system with a yielding force P_y = 2670 kN;
2. Threaded bar hardware (couplers & nuts) all capable of safely withstanding 125% of bar yield strength;

3. Micropile top casing is 324 mm diameter steel tubing as per ASTM A53;
4. Micropile grout is neat Type GU cement, with a minimum 28-day yield strength f'_g = 35 MPa.
5. Bearing plates were steel plate with minimum grade of 350 MPa.

The profile of the micropiles beneath the north abutment (with BH4 shown for reference) is shown in Figure 6. The subsurface profile of the micropiles beneath the south abutment (with BH2 shown for reference) is shown in Figure 7.

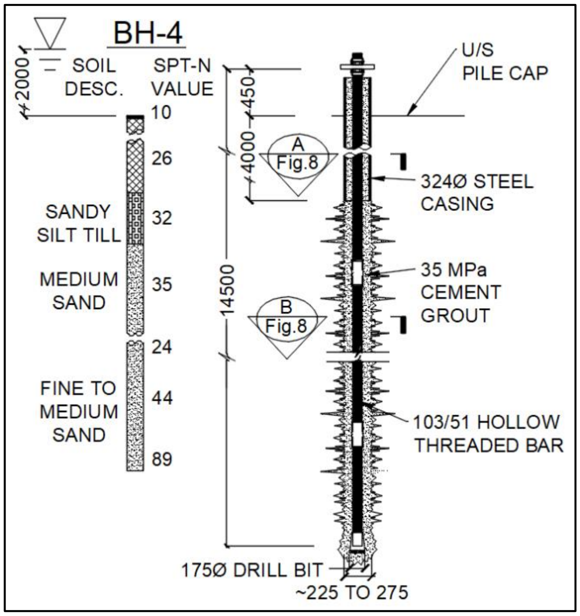

Figure 6. Profile of a typical north abutment micropile, with BH4

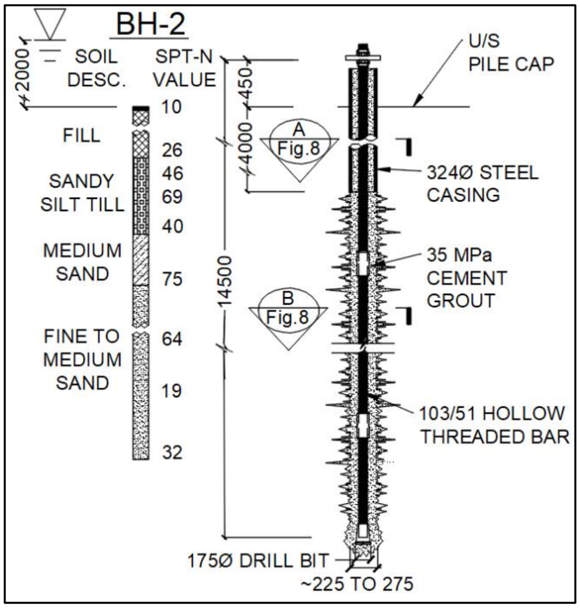

Figure 7. Profile of a typical south abutment micropile, with BH2

Figure 8 shows the cross sections A and B in Figures 6 and 7 highlighting the details of the micropiles. A cased length of 4m was used for all micropiles.

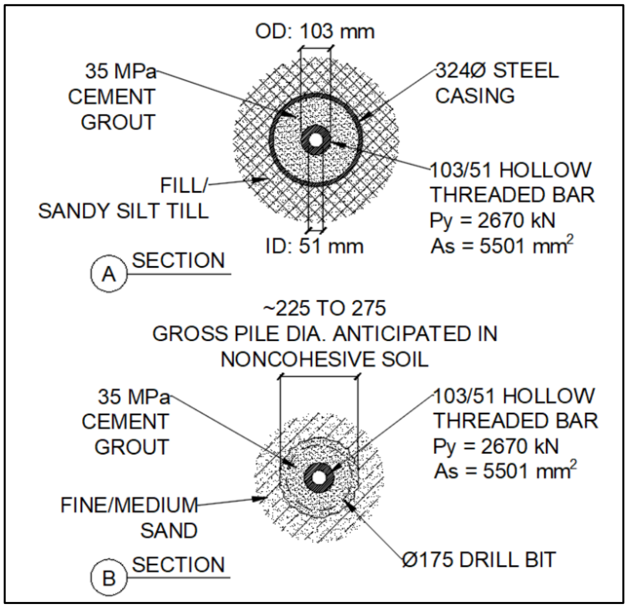

Figure 8. Cross-sections of the micropiles

The design of the micropiles and the calculation of their bearing capacity were conducted in adherence to “Micropile Design and Construction Guidelines” published by US Federal Highway Administration (FHWA 2000). Load Factor Design (LFD) method was used for the design. The following design parameters and assumptions were used to calculate the micropiles’ capacities.

Considering the mechanical properties of all components of the micropiles and aforementioned design parameters, the factored axial compression load (in terms of strength) of each micropile at ULS is 1070kN and the factored axial tension load of each micropile is 325kN and compression load is 700kN at SLS as assigned by the Structural Engineers.

The installation procedure is summarized as follows:

1. Prior to drilling of the hollow core bar, a 356 mm diameter auger was used to advance a hole to a depth of 4 m below the underside of the proposed pile cap.
2. Upon withdrawal of the auger, the hole was immediately filled with cement grout and an open-ended permanent steel casing was set into place, full of grout. The casing was left undisturbed for a minimum 24 hours.
3. The hollow bar reinforcement was then advanced through the soil using continuous-grout-flushed method. Grout was pumped through the flushing head and exited the drill bit under continuous pressure to maintain a full head of grout at all times.

Figure 9 shows two completed production micropiles including the hollow bar reinforcement and the casing before the installation of the bearing plates.

Figure 9. Two completed production micropiles

6. PRE-PRODUCTION LOAD TESTS – RICHCMOND HILL GO

Two performance load tests were carried out on sacrificial micropiles to verify the key assumed geotechnical design parameter (i.e. grout-to-ground adhesion). Each of the two sacrificial test piles was embedded near each abutment to ensure embedment in representative soil profiles. The sacrificial test piles were designed to resist ULS compression loading of 1070kN and ULS tension loading of 325kN. In addition to these performance criteria, all micropiles were designed to meet the structural engineer's stiffness of SLS compression loading of 700kN. The setup of the test piles is illustrated in Figure 10.

Figure 10. Load test arrangement

Tension load tests were used to validate the micropile capacities in lieu of compression tests. The performance test piles were loaded to two times their design load (i.e. to 2000kN) value at ULS. Tension load test method according to ASTM 3689 Procedure A - Quick Test Method was followed to determine the micropile capacity. In addition, cyclic loading between 300kN and 700kN was performed. Four loading phases were applied. The details of these loading phases are summarized as follows.

<u>Phase 1 Load Testing:</u>

Applied static tension load to the test pile in increments of 100 kN, as follows: 0, 100 kN, 200 kN, 300 kN, 400 kN, 500 kN, 600 kN, 700kN;

Held each new load for a minimum of 10 minutes and recorded movement readings for each load at 0.5, 1, 2, 4, and 8 minutes except at the 700 kN load increment where the load was held for a minimum of 600 minutes with readings taken at 0.5, 1, 2, 3, 4, 5, 6, 8, 10, 15, 20, 30, 45, 60, 80, 100, 120, 180, 240, 300, 360, 420, 480, 540 and 600 minutes. At the conclusion of the 600 minutes hold at 700 kN, Phase 2 Load Testing commenced.

<u>Phase 2 Load Testing:</u>

Started at the end of Phase 1 Load Testing (i.e. with 700 kN applied tension force already applied to the test pile), applied cycled static loading as follows: 700 kN, 500 kN, 300 kN, 500 kN, 700 kN, 500 kN, 300 kN, 500 kN, 700 kN, 500 kN, 300 kN, 500 kN, 700 kN;

Held each new load increment for a minimum of 20 minutes and took readings at 1, 2, 3, 4, 5, 6, 10 and 20 minutes. At the conclusion of the 20-minute hold at the final 700 kN increment, proceeded directly to Phase 3 Load Testing.

<u>Phase 3 Load Testing:</u>

Started at the end of Phase 2 Load Testing, applied incremental static loading as follows: 700 kN, 800 kN, 900 kN, 1000 kN, 1100 kN, 1200 kN, 1300 kN, 1400 kN, 1500 kN, 1600 kN, 1700 kN, 1800 kN, 1900 kN, 2000 kN;

Held each new load for a minimum of 10 minutes and recorded movement readings at each load at 0.5, 1, 2, 4, and 8 minutes except at the 2000 kN load increment where the load was held for a minimum of 60 minutes with readings taken at 0.5, 1, 2, 3, 4, 5, 6, 8, 10, 15, 20, 30, 45 and 60 minutes. At the conclusion of the 60 minute hold at 2000 kN, proceeded directly to Phase 4 Load Testing.

<u>Phase 4 Load Testing:</u>

Started at the end of Phase 3 Load Testing (i.e. with 2000 kN applied tension force already applied to the test pile), reduced the load on the test pile in decrements of 200 kN as follows: 2000 kN, 1800 kN, 1600 kN, 1400 kN, 1200 kN, 1000 kN, 800 kN, 600 kN, 400 kN, 200 kN, 0;

Held each new load for a minimum of 10 minutes and recorded movement readings at each load at 0.5, 1, 2, 4, and 8 minutes except at 0 loading where readings were taken at 1, 2, 4, 8, 15 and 30 minutes. Figures 11 and 12 presents the load test results.

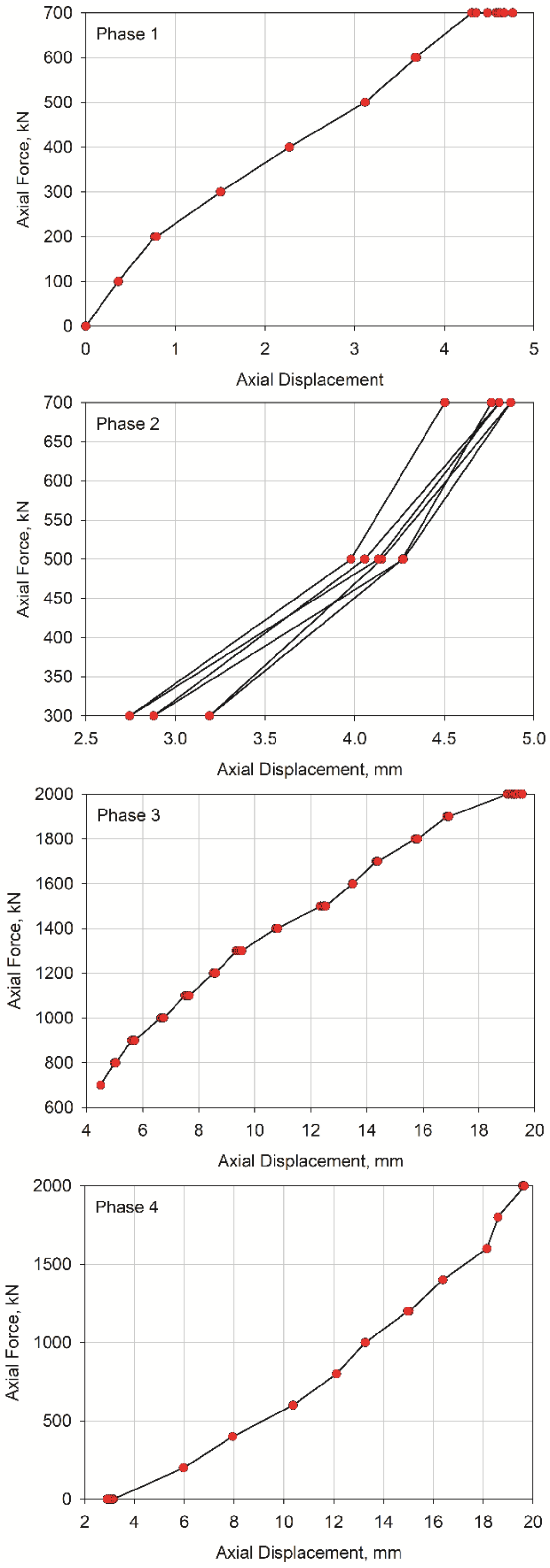

Figure 11. Results from the sacrificial pre-production test micropile near the north abutment

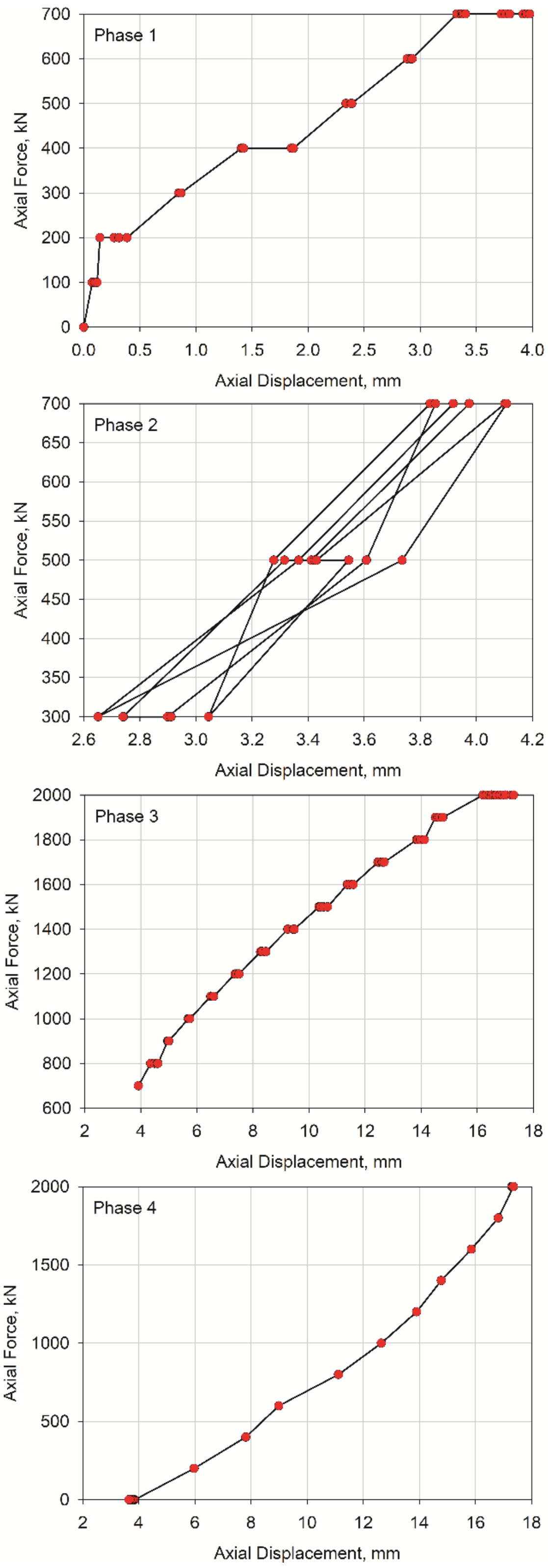

Figure 12. Results from the sacrificial pre-production test micropile near the south abutment

It can be observed from Figures 11 and 12 that the development of micropile displacement was continuous and stable when loaded. The maximum displacement for both micropiles at 2000kN was less than 20mm. The micropiles can withstand 2000kN tensile loading, which is twice its design capacity without geotechnical failure.

Using the test results summarized in Figures 11 and 12, the maximum grout-to-soil adhesion values achieved were 364 kPa and 421 kPa at the north and south abutments, respectively during the pre-production load tests.

7. CONCLUSIONS

A unique approach to constructing deep foundations that must penetrate artesian aquifers has been performed and validated at an urban transportation infrastructure project in Ontario. Further, it has been shown that the continuous grout-flush micropile construction process employing cement grout at specific gravity $\geq 1.85 g/cm^3$ was effective in managing both of the two biggest risks associated with penetrating artesian aquifers: washout during construction was eliminated by the heavy grout column; and post-installation piping was eliminated by the roughness and integrity of the grout-to-ground interface having sufficient resistance to prevent any piping-induced apertures from ever forming. Pre-production tension load tests verified the suitability of the installation technique and confirmed the basis of the design. The installation technique detailed in this paper should be helpful to provide a safe and reliable process for future deep foundations construction where artesian aquifers must be penetrated.

REFERENCES

ASTM (2013) D3689 / D3689M-07, “Standard Test Methods for Deep Foundations Under Static Axial Tensile Load.” ASTM International, West Conshohocken, PA.

Bruce, J. and Gurpersaud, N., (2009). “Grout-flushed micropile foundations for a new rail overpass.” Proceedings of the 9th International Workshop on Micropile (IWM) 2009, London, England.

Fetter, C.W. (2001). “Applied Hydrogeology.” Fourth Edition, Prentice-Hall Inc., Upper Saddle River, New Jersey.

FHWA (2000) “Micropile Design and Construction Guidelines.” US Federal Highway Administration, Implementation Manual, Publication No. FHWA-SA-97-070, June 2000.

SPL (2015) “Preliminary Recommendations, Micropile Foundations for Re-Deign of GO Station Pedestrian Platform Extension over Major Mackenzie Drive” SPL Consultants Limited, Toronto, ON.

TRL (1993) “The Development of Specifications for Soil Nailing” UK Transportation Research Laboratory Report 380.