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Application of High Capacity Soil-Bonded Micropiles in the Greater Toronto Area

by

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ABSTRACT

The market for micropiles in the Greater Toronto Area (GTA) continues to expand, with over 100 projects in the ground since 2001 and more projects being built on micropiles than ever before.

While much of downtown Toronto is underlain by sound shale bedrock within 15 metres of surface, midtown Toronto and the densely developed belt of the city to the north have no rock within 30 metres of surface. While rock-socketed micropile design values are well established for Toronto geology, design values for grout-to-ground bond stress for soil-bonded micropiles remain proprietary to the small number of local micropile practitioners that continue to advance the local state of the art.

Specialized drilling, installation and grouting methods, in combination with high level QA/QC, have resulted in the successful application of high capacity soil-bonded micropiles as the deep foundation elements for several challenging projects within the GTA. Results obtained from soil-bonded micropiles at 4 sites, constructed using different installation methodologies and all highly loaded during pre-production static compression testing, are presented. Detailed analyses of the results obtained, with corresponding sub-surface profiles and comparison to values taken from the USFHWA Micropile Implementation Manual, are outlined in this paper.

1.0 INTRODUCTION

The Toronto construction market continues to enjoy sustained growth due to government infrastructure spending and a robust housing market driven by Toronto's status as the top destination for new immigrants to Canada. As developers continue to seek out prime real estate for high rise housing developments, many such projects are being built on sites to the north of downtown Toronto where the geology is characterized by glacial soil deposits and significant depths to rock. Due to their growing recognition and acceptance within the local geotechnical consulting community, micropiles are being considered and increasingly utilized for applications in the condominium housing market, including sites where the micropiles must develop high loads despite depth to rock precluding the consideration of rock-socketed foundations.

2.0 TORONTO AREA GEOLOGY

Subsurface conditions in Toronto are, for the most part, attributable to the cyclical history over the last 100 000 years of multiple episodes of deposition and subsequent loading due to receding and advancing continental glaciations. The overburden materials throughout this region consist of overconsolidated glacial deposits of silt, clayey silt and moderately cemented sand/silt/clay till. The granular deposits are generally compact to very dense and the cohesive deposits are generally stiff to hard. Lenses of saturated granular soils (silts & sands) are often encountered within layers which are otherwise, for the most part, impervious. These soils generally exhibit good to excellent engineering behavior and are well suited to economical foundations such as spread footings or short friction piles. Downtown Toronto is bordered to the south by Lake Ontario, with the city sprawling northward away from the lake. While depth to rock in the downtown core is typically less than 15 m below surface, overburden thickness at the southern end of midtown Toronto (3.5 km from the lake shore) is over 30 m and increases significantly as one moves north.

3.0 CASE STUDY #1 – BLOOR STREET WEST, 2007

3.1 Project Background

This project, located in the trendy and popular Yorkville area of midtown Toronto, featured micropiles constructed in the basement of an existing, circa 1950's, 13-storey tower. The existing tower, with 2 basement levels below grade, was retrofitted for a 6-storey vertical expansion to construct high-end luxury residential apartments. Support for the new space was carried downwards via plate-reinforcing of existing steel columns, supported in turn by existing pad footings augmented with micropiles. A total of 46 micropiles were constructed to augment 11 existing pad footings. The new mode of foundation load resistance was a hybrid between bearing at the underside of the footings and supplemental resistance provided by the micropiles.

3.2 Subsurface conditions

Relative to the underside of existing footings, the subsurface profile (Fig. 1) consists of 6 m of Queen's Park Varved Clay, a very stiff, silty clay with thin, dry laminations of very fine sand, underlain by the Queen's Park Stratum, a dense glacial till consisting of a sand silt matrix with gravel and cobble inclusions. From known borings outside of this project's investigations, the depth to groundwater is 9 to 10 m and the depth to bedrock exceeds 30 m.

3.3 Micropile Design Approach

Individual micropile loading was 1000 kN (service) axial compression, at which magnitude the quantity of piles at any one augmented footing could be limited to four. Micropiles were not required to resist uplift or lateral loads. Although headroom restrictions were typical throughout the work and as severe as 2.5 m at some locations, the governing condition, present at half of the micropile locations, was access and working footprint, necessitating the use of a mast-only drill (with remote power pack) fastened to the existing structure. In order to locate the respective pile-to-footing connection structures within the available vertical envelope between the footing and finished floor, the micropiles were drilled inside the respective footprints of the augmented footings. With access limiting the size and capability of the drilling equipment and open-hole drilling being inappropriate beneath the in-service existing footings, non-percussive rotary boring with synthetic mud flush was used to drill the 225 mm diameter micropile holes. Given the relatively high magnitude of loading and the necessity for the micropiles to be slender and soil-

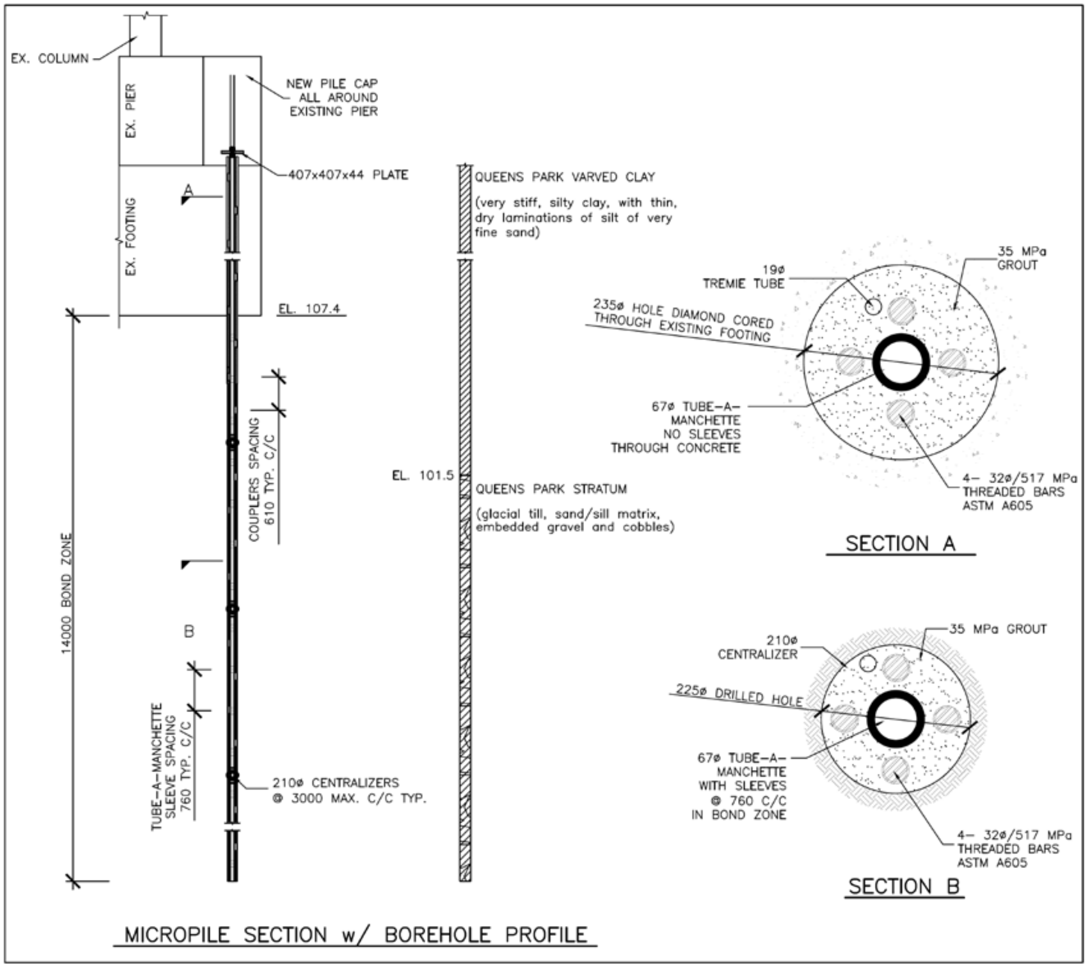

FIG. 1 Sacrificial pre-production micropile section and soil profile at the 130 Bloor W. project

bonded, post-grouting using the most assured method – tube à manchette with double gland packer – was used to post-grout the entire bond zone. With the post-grouting capability established as a key component of the micropile design, combined with the fact that hoisting of heavy components would prove problematic given the cramped quarters in which most of the piles were constructed, the micropile cross section was designed as a 4-32ø / 517 MPa threaded bar arrangement surrounding a 67ø tube à manchette, and the micropiles were designed without any permanent casing.

3.4 Sacrificial, Pre-Production Micropile

It was self evident due to physical constraints that load testing of any production micropile was completely impracticable, and accordingly, a representatively constructed, sacrificial, pre-production test micropile was installed and loaded in cycled static compression in increments of 250 kN to a test load of 3000 kN, or 300% of micropile design load. Post-grouting of the 16 m deep test micropile was performed in two passes, with the first injection taking place between 12 and 16 hours after tremie grouting and the second pass 6 hours after the first. Injection pressures and grout takes were monitored and recorded for every sleeve during both passes. The low frequency of testing, especially in light of the fact that these were soil-bonded micropiles, was offset by the high magnitude of loading. The test micropile succeeded in resisting the test load; load test results are detailed further in Table 1.

4.0 CASE STUDY #2 – SKYY CONDOMINIUM, 2008

4.1 Skyy Project Background

Minto Skyy is a glass-clad 23-storey tower that overlooks downtown Toronto from its perch atop the walls of the Don Valley. The tower occupies a site that, before construction, sloped so steeply that the excavation support system varied in terms of height of retention from 17 m at the Broadview Avenue frontage to just 7 m at the northern extent of the Pottery Road frontage. The original foundation design called for spread footings throughout, but a changed condition discovered during excavation necessitated the introduction of large diameter drilled shafts, in groups of three, to support loads in the south and southwest portions of the tower footprint. When the same changed condition necessitated the emergency installation of augmentative, large diameter corner bracing (Fig. 2) to arrest troubling movements at the southwest corner of the excavation support system, a new restrictive headroom condition was created and the drilled shafts in this area were replaced with micropiles.

4.2 Skyy Soil Conditions

The majority of the tower footprint is underlain by dense clay till capable of supporting pad footings of 700 kPa bearing. At the location of the micropiles, the ground conditions varied significantly relative to the balance of the tower footprint, with layers of soft, loose, clayey silt / silty clay as deep as 9 m below underside of pile cap, and the top of the groundwater table within 2 m of underside of pile cap. Relative to underside of pile cap, the depth to the competent soil ranged from 7 to 10 m, after which the soil conditions transitioned very quickly to hard clayey silt till.

4.3 Skyy Micropile Design Approach

Beyond the fact that the micropiles would be soil-bonded and not rock-socketed, two key drivers of the micropile design were immediately self evident: restricted headroom and the thick soft soil layer. The presence of the corner bracing meant that at least half of the micropiles would have to be constructed directly beneath an overhead obstruction at 5.5 m above drilling grade. The 1000 kN compression service load and the presence of the 7 to 10 m thick soft layer made certain that the micropiles would all feature a substantial casing over at least their uppermost 8 m of embedment. The final driver of the design was the close pile-to-pile spacing required in order to arrange a sufficient quantity of piles beneath the heaviest loaded pile caps: this factor meant that the process used to drill the bond zones had to be selected to avoid unduly energizing any freshly grouted pile while in the act of drilling its neighbour pile.

4.4 Skyy Sacrificial, Pre-Production Micropile

One representatively constructed, 20 m deep, pre-production sacrificial micropile was constructed and load tested to 2000 kN. The installation process involved three distinct steps. For the first step, 10 m of permanent casing was advanced using double-head duplex drilling method, with 245ø / 550 MPa, left-hand threaded-joint casings rotated by the upper drill head and a 203ø drag bit, vertically offset relative to the casing tip in order to maintain a protective soil plug ahead of the drag bit, rotated in right-had rotation by the lower drill head. Cuttings were flushed clean using compressed air delivered through the drag bit. For the second step, the 203ø bond zone was drilled beneath the casing tip using synthetic polymer mud flush. For the third and final step, a single 57ø / 517MPa threadbar, complete with centralizers and tremie grout tube, was installed in the mud-charged hole, tremie grouted until all mud was expunged from the hole and then the pile was pressure grouted through the casing until grout was forced to the surface on the outside of the casing. The sacrificial test micropile was successfully load tested to 2000 kN (200% of design load); load test results are listed in Table 1.

FIG. 2: View of the southwest corner of the Skyy project – note the large corner brace at 6 m above grade

5.0 CASE STUDY #3 – SOLARIS, 2008

5.1 Solaris Project Background

Solaris 1 and Solaris 2, twin 40-storey residential towers at Kennedy Road and Highway 401, are part of a 17 acre sustainable community development called Metrogate. Approximately 40% of the property line borders the busy Canadian Pacific Railway right of way. With construction due to start in 2009, the developer commissioned the design, installation and load testing of a prototype micropile in early 2008 to assist in choosing the most cost-effective foundation scheme to support the towers.

5.2 Solaris Soil Conditions

The site features a high groundwater table. The surficial geology is predominantly medium dense till soils with high sand content. For the proposed twin towers, pad footings were precluded due to the relatively low bearing available within the uppermost few metres and the high cost of dewatering in order to excavate to a more competent bearing horizon. The dewatering / excavation option also came with the very real risk of being rejected outright by the railway due to its potential influence on railway embankment stability. The decision ultimately facing the developer was whether to found each tower on a raft slab, requiring relatively little dewatering, or on micropile-supported pile caps in place of pad footings.

5.3 Solaris Micropile Design Approach

The structural engineer identified 450 kN of axial service compression as the optimized pile loading. Given the high groundwater table, the sandy silt character of the bond zone soils and the relatively light pile loading, hollow-bar grout-flush was selected as the installation process. While ostensibly the purpose of the load test was to induce geotechnical failure, there was significant value to be had by conducting the loading in static compression so that, as well as pinpointing the precise failure load, the test micropile's performance under load could be precisely measured. For this reason, the pile was embedded at a depth estimated to be short enough to achieve geotechnical failure yet deep enough to be sufficiently representative of the most likely micropile configuration to be proposed if the test pile performed as anticipated.

5.4 Solaris sacrificial, pre-production micropile

A Titan 52/26 hollow bar with 115 mm diameter cross-cut drill bit was embedded plumb, 12 m below surface. Flush grout was normal Portland cement mixed at 0.7 water/cement (by weight), and switched during advance of the last 2 m to 0.45 w/c. The permanent casing was 140 mm diameter x 2.5 m deep. The micropile passed all acceptance criteria through the 900 kN (200%) loading cycle (Fig. 3), but began plunging during the attempted hold period at the 1200 kN (267%) loading cycle.

6.0 CASE STUDY #4 – HULLMARK CENTRE, 2010

6.1 Hullmark Project Background

Scheduled for completion in 2014, the Hullmark Centre project is a large commercial-residential development featuring two office towers, 5 and 7 storeys respectively, and two condominium high rise towers, 37 and 45 storeys, respectively. The northeast corner of the site is co-owned between the developer and the Toronto Transit Commission (TTC), where it overlaps a buried wye railway tunnel and emergency exit building. Both TTC structures were required to remain in service throughout construction. Although street level at this area will become a pedestrian boulevard, a 2-storey mezzanine will overhang this space and be founded on micropiles. Also located at the northeast corner is a new pedestrian tunnel to link the existing TTC Sheppard Station with the Hullmark Centre P3 parking level, and this tunnel will also be founded on micropiles. Beyond knowing of micropiles' existence in the local marketplace, very little was known about micropiles, and soil-bonded micropiles in particular, by the developer, the developer's various consultants, and the TTC. Ultimate approval of the entire proposed development was held up for several months during 2008-2009 by the TTC on account of its lack of comfort with the viability of micropiles at this site, both in terms of available capacity and means by which the micropiles could be constructed to ensure a complete absence of load transfer from the micropiles onto the TTC's several and various existing buried structures. At this juncture, seemingly stalemated, the developer commissioned the design, installation and testing of a prototype micropile.

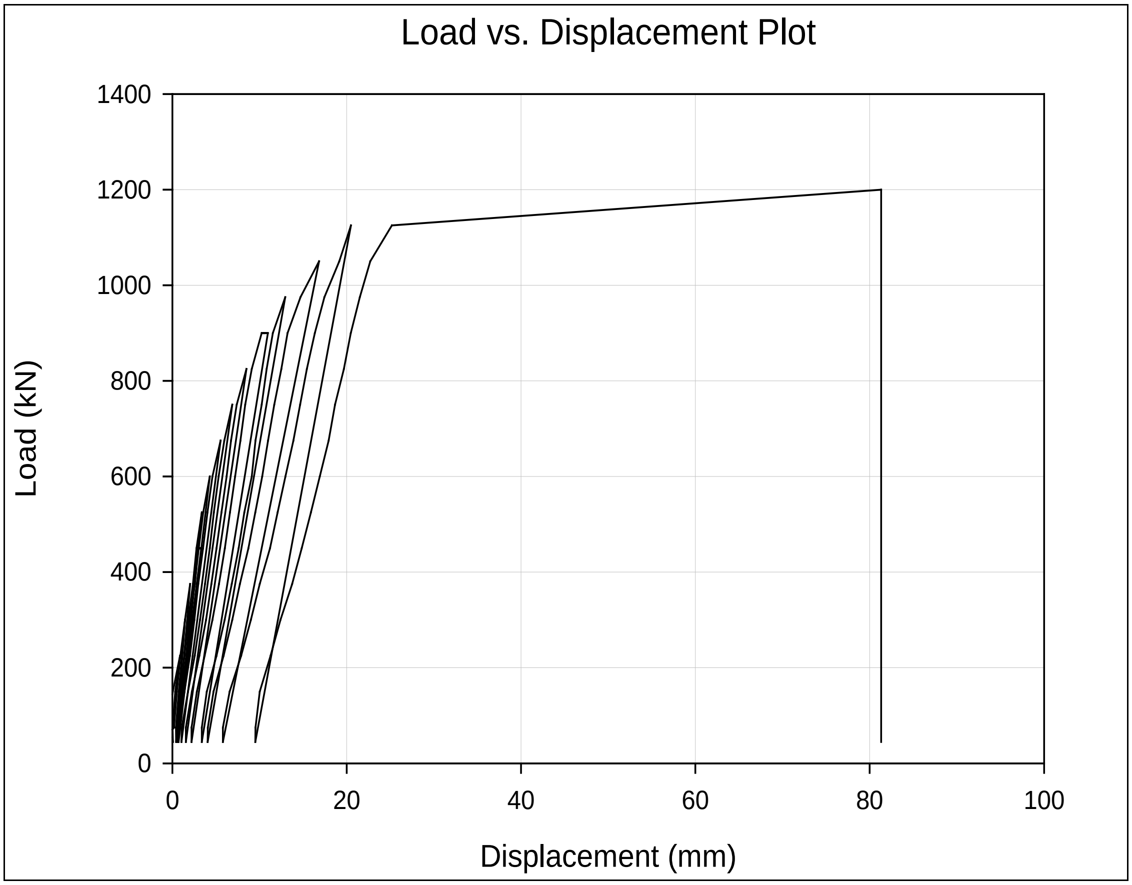

FIG. 3: Load vs. movement plot – Solaris sacrificial test micropile

6.2 Hullmark Soil Conditions

Micropiles cut off elevations range from 167.2 m (geodetic) to 173.0 m. The undersides of the various TTC structures terminate at 162.0 m. In the vicinity of the wye structure, relative to elevation 171.0 there is 3 to 4 m of fill, underlain by 5 m of dense brown sand, underlain by 7 m of hard grey sandy silt transitioning to clayey silt, underlain by very hard clayey silt till with gravel inclusions.

6.3 Hullmark Micropile Design Approach

The owner's hope for the prototype micropile was to prove that an 800 kN service load micropile could adequately perform with respect to stiffness and capacity. The micropile contractor set out to prove at least 1200 kN and hopefully as great as 1600 kN allowable compressive loading. In addition to these goals, it was absolutely non-negotiable in order to satisfy the TTC that the micropile must also transfer no load above the horizon coincident with the underside of the TTC's various buried structures. Considering that the site of the proposed permanent micropiles included a hornets' nest of buried services amongst and above the buried TTC structures, there was certain value in proving a higher micropile capacity, because this could be parlayed into reducing the quantity of micropiles, and thereby the number of attempted penetrations through and past the buried elements, required to construct the project. With no bonding allowed above 161 m and some of the cut off elevations as high as 173 m, a thick-walled permanent casing had to be incorporated into the design, both to double as a means of stiffening the unbonded portion of the micropile and, by virtue of the annular space between the outside of the casing and the hole wall, as a means of unbonding the upper reaches of pile using an incompressible but very low shear strength bentonite-cement grout. With the design load possibly as high as 1600 kN, a single 75ø /517 MPa threaded bar was used as the full length reinforcement and, for relatively little added cost and potentially significant benefit, a tube à manchette post grouting system was embedded in the pile for aggressive post grouting of the bond zone. In consideration of the fact that the micropiles would be drilled near and beneath existing structures, the holes were drilled using non-percussive rotary boring with synthetic mud flush, with a 305ø hole size to enable a minimum 13 mm annulus after insertion of the 273ø casing.

6.4 <u>Sacrificial, Pre-Production Micropile</u>

Construction and testing of the prototype micropile was undertaken on an early works basis, prior to any other construction activity on the site. As such, the micropile was installed from top of pavement at an operating parking lot, at 174.7 m and the pile was cased to a depth of 15 m to ensure that the 10 m bond zone was drilled in a suitably representative soil layer. Load test results are listed in Table 1. The test was successful in proving both the high capacity of the soil-bonded micropile (Fig. 4) and the purely elastic

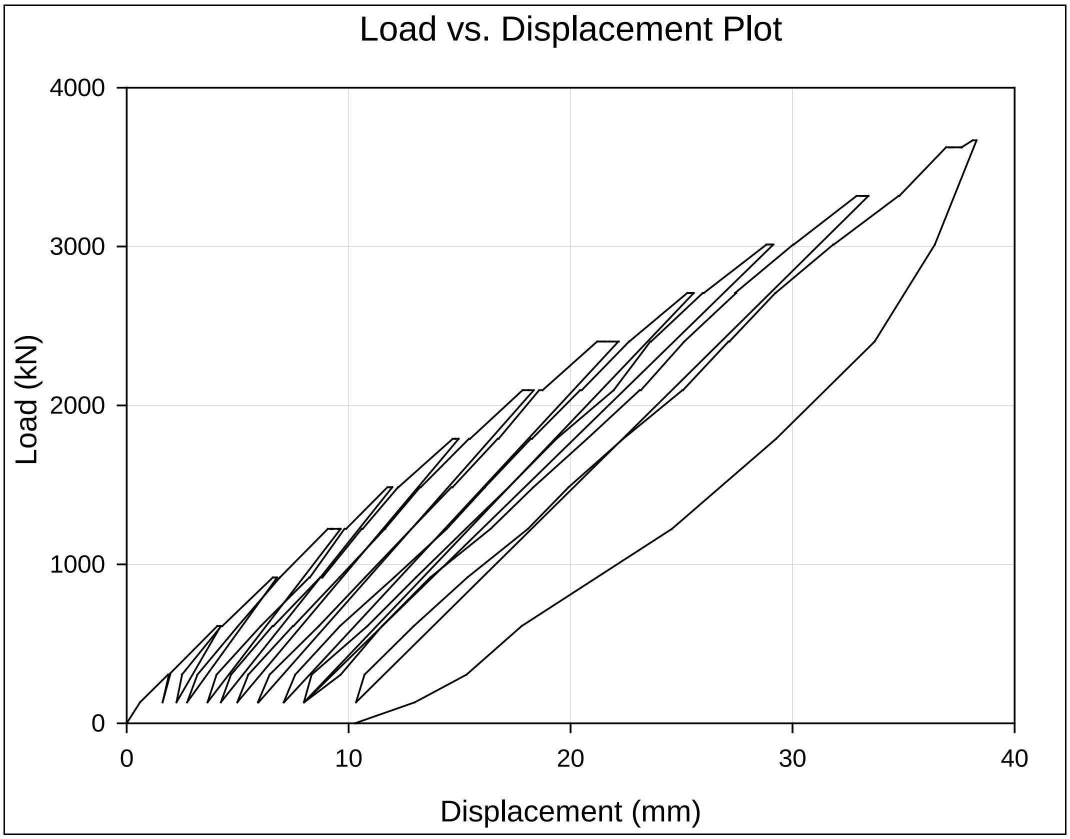

FIG. 4 Load vs. movement plot – Hullmark Centre sacrificial test micropile

compression of the cased portion of the pile under applied loading, which proved that the uppermost portion of micropile could indeed be constructed in a manner that enabled no load transfer to the surrounding soil. The prototype design was adopted for use as the permanent micropile design.

7.0 SUMMARIZED LOAD TEST RESULTS

A detailed summary of the test results obtained from sacrificial pre-production micropiles at the 130 Bloor Street West, Skyy, Solaris and Hullmark projects are presented in Table 1.0. All tests were performed in cycled, static compression, in general conformance with ASTM D1143, with their respective load frames tied down using 4 tension micropiles or 4 post-tensioned soil anchors.

TABLE 1.0: Summary of soil-bonded micropile load test results

PROJECT	130 BLOOR	MINTO SKYY	SOLARIS	HULLMARK
Primary reinforcement	4-32 Ø / 517 MPa threaded bars	57 Ø / 517 MPa threaded bar	Titan 52/26 hollow bar	75 Ø / 517 MPa threaded bar
Total Micropile Embedment (m)	16	16.5	12	25
Bond zone length and diameter (m / mm)	14.0 / 203	10.0 / 203	12 / 173	10.0 / 305
Bond zone medium	Varved clay and dense glacial till	Hard clayey silt till	Dense sandy silt	Dense glacial till
Drilling method	Non-percussive, synthetic mud flush	Non-percussive, synthetic mud flush	Top-hammer, continuous grout flush	Non-percussive, synthetic mud flush
Grouting method	Gravity grouting, followed 12 hours later by 2 passes of targeted post grouting	Gravity, with limited-quantity pressure grouting through casing	Dynamic (continuous grout flush)	Gravity grouting, followed 12 hours later by 2 passes of targeted post grouting
Design Load, DL (kN)	1000	1000	450	1200
Max. Test Load (kN)	3000	2000	1200	3600
Max. Test Load (% DL)	300%	200%	267%	300%
Micropile Failure Mode and Load	Creep failure at 3000 kN	No pile failure	Plunging at 1200 kN	No pile failure
Failure Load (% of Design Load)	300%	N/A	267%	N/A
Max. bond stress achieved (kPa)	305	317	332	376
FHWA bond stress values for similar sub-surface conditions (kPa)	120 - 335	50-120	70 - 145	95 - 240
Hold time at Test Load (mins.)	60 (3.0 DL)	60 (2.0 DL)	40 (2.0 DL)	60 (3.0 DL)
Creep (6 to 60 mins) at Test Load (mm)	2.6 (3.0 DL)	1.00 (2.0 DL)	not measured	0.65 (3.0 DL)
Gross displacement at 1.0 DL (mm)	5.2	7.7	3.3	9.6
Gross displacement at Test Load (mm)	49.4 (3.0 DL)	32.9 (2.0 DL)	25.2 (2.5 DL)	38.12 (3.0 DL)

8.0 DISCUSSION AND CONCLUSIONS

The results presented in Table 1 clearly demonstrate the viability of high capacity soil-bonded micropiles embedded in soils typical of the Toronto area.

Static compressive load testing of sacrificial micropiles provides data with respect to stiffness and ultimate capacity that simply cannot be gleaned from data compiled during proof testing of production micropiles in tension. Although compressive testing is many factors higher in terms of cost relative to tension testing, there is no comparison with respect to the quality of information obtained. Especially in the case of soil-bonded micropiles, a sound case can be made for justifying the higher cost associated with compression testing, simply by recognizing that the data truly represents how a similarly constructed production micropile should behave when in service, rather than inferring its behaviour with several haphazardly assigned correction factors.

The technical and economic advantages associated with the use of micropiles have contributed to the increasing popularity of this formerly obscure technology in the local Toronto marketplace. This popularity is both validated and bolstered by the increasing number of successful micropile load tests, especially with respect to high capacity, soil-bonded micropiles embedded in typical Toronto area glacial till soils.

Specialty contractors are acquiring the best available tooling and utilizing most current grouting practices in order to construct micropiles that can be demonstrated, via successful high magnitude load testing, to achieve higher than expected bond stresses. Although the results shown in Table 1 may seem to demonstrate that the USFHWA estimates of capacity per general soil type are excessively conservative, it must be noted that absolute best practice, in terms of drilling and grouting methods, was employed in constructing the test micropiles whose load test results are detailed in this paper. As such, although the USFHWA estimates may perhaps in some ways be outdated, more time is required to allow the micropile market to develop further before any change to the published estimates will be warranted.

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