GROUT FLUSHED MICROPILE FOUNDATIONS FOR A NEW RAIL OVERPASS

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ABSTRACT

Micropiles remain an emerging technology in the Greater Toronto Area (GTA) market in Canada due to a variety of factors including a well deserved reputation for costliness relative to conventional deep foundation types. Ironically, when micropiles were proposed post-tender in place of the specified driven pile scheme for a railway infrastructure project, it was the cost effectiveness and cost certainty of the micropile scheme that ultimately lead to its acceptance.

The CPR Morningside Grade Separation Project went to tender on driven tube piles, specified to be terminated no deeper than 4 metres below underside of structure in order to avoid penetrating into an aquifer under artesian head. Grout-flushed micropiles, whose stiffness is primarily derived geotechnically rather than structurally, and whose capacity is derived from grout-to-ground adhesion rather than end bearing, were constructed in place of the tendered driven piles with great success.

This project is exemplary of many aspects of the struggle for micropiles to gain traction in the GTA for two core reasons. First, although this project was poorly suited to driven piles and ideally suited to micropiles, micropiles were never truly considered by the owner due to the continuing unwillingness on the part of both the local engineering and foundation contracting communities to embrace micropiles. Second, had micropiles been designed by the owner in a manner suitable for the scheme to be loosed on the contracting public at large, the design would have been so necessarily conservative as to be impractical and infeasible.

This paper details the project site conditions and micropile design considerations, and provides commentary that details the various motivations of the owner in designing and tendering the driven pile scheme, the general contractor in promoting the micropile alternative, and the micropile subcontractor in accepting the level of risk that was required to ultimately win the job.

INTRODUCTION

The continuing extensive growth and development of the Greater Toronto Area, Canada, is driving demand for modifications to existing railway infrastructure. Prior to the summer of 2008, Toronto’s Morningside Avenue was restricted by a decades-old, single lane underpass at its crossing of the Canadian Pacific Railway (CPR). A grade separation was constructed in 2008 to create a six-lane subway beneath the CPR, necessitating construction of seven new, deep-founded structures (2 abutments, 1 pier and 4 retaining walls) (Figure 1). The continuing, uninterrupted operation of both the railway and the roadway were integral components of the grade separation construction scheme, and the contract documents stipulated that no temporary rail diversion could be constructed. To facilitate this approach three full depth excavations – one each for the east abutment, centre pier and west abutment – were constructed concurrently, all the while maintaining uninterrupted rail and road service (Figure 2). This approach resulted in particularly challenging geometry with respect to access to the underside of the principle structures to be piled. Shoring wall to shoring wall spacing was just 8 metres, and bracing struts crowded the already limited headroom, creating a series of longitudinal (relative to the tracks) overhead obstructions just 6 metres above the grade from which piles were to be installed.

The project went to tender with the structures specified to be founded on driven, 324mm diameter steel tube piles ($A_s = 12409 \text{ mm}^2$). The site is underlain by a significant aquifer under artesian head, and the tendered driven pile design was predicated on terminating the piles at a pre-determined, safe distance above the top of the aquifer. Following the specification would have resulted in the deepest pile being embedded only 4.0 metres below underside of structure, regardless of any determination of pile capacity. Post-tender, a micropile alternative – using 52mm diameter hollow bars ($A_s = 1337 \text{ mm}^2$) in roughly a 5: 3 (micropiles: driven piles) substitution ratio, installed to similarly restricted embedment depths using the grout flush installation process – was successfully proposed.

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After decreasing individual pile loading by increasing pile quantity, grout-flushed micropiles, with their stiffness derived from aggressive bonding into the soil rather than their cross sectional bulk, and their capacity derived from grout-to-ground friction rather than end bearing resistance, provided an ideal solution for satisfying the seemingly disparate dual objectives of assuring pile capacity while avoiding aquitard breach. Eventually, after the prospective micropile subcontractor agreed to perform no fewer than five static load tests to prove the merits of the proposed micropile design, and agreed to hold the piling price with no claim for extras pending whatever load test results might come, the piling scope was awarded based on the micropile alternative.

SUBSURFACE CONDITIONS

Two predominant soil deposits exist at this site within the depth originally investigated to determine potential foundation options. The upper layer consists of silt glacial till with occasional cobbles. The lower layer consists of a sand deposit which in some places grades to sand and gravel. This lower layer is an aquifer under artesian head. The combined characteristics of the upper soil layers and the prevailing ground water table ruled out the use of
shallow foundations for the proposed structures. Numerous difficulties were encountered during the pre-project subsurface exploration, alerting the project’s designers to the challenges awaiting conventional deep foundation design. Consequently, the depth of pile penetration was restricted to the upper till layer in order to mitigate the risk of puncturing through the underside of the till layer into the aquifer. Subsurface profiles are shown in Figure 3.

![Figure 3: Subsurface Profiles](image)

**MICROPILE VALUE ENGINEERING PROPOSAL**

The prime contract for this project was awarded prior to the micropile subcontractor ever approaching the general contractor regarding an alternative piling scheme. At time of prime contract award, both the general contractor and the owner were apprehensive towards multiple aspects of the tendered driven piling scheme. The project was on an extremely aggressive schedule, with piling on the critical path, and the 324mm diameter tubing required for the driven piles required several weeks’ lead time ahead of delivery to site. Overshadowing this logistical concern were the general contractor’s and owner’s own past experiences with driven pile quantities exceeding contract estimates, resulting in contentious claims for extra payment, and their collective aversion to contemplating contingency plans in the event that any of the driven piles did not satisfy its set criteria when driven to the maximum allowable depth. Most concerning of all were the self evident problems arising from having to install driven piles within the confines of such a
restricted site, with the requirement to keep rail traffic uninterrupted, no less. When the micropile scheme was proposed, the general contractor and owner were willing to listen.

Multiple benefits associated with the proposed micropile alternate appealed to the general contractor and owner. The scheme used off the shelf materials whose delivery to site could be arranged within one week. The scheme could be constructed with small equipment able to operate in low headroom. No changes were required of the pile caps or any other component of the superstructure. More piles equated to greater redundancy of foundation design. The micropiles could be embedded significantly deeper than the 4 metres assigned to driven piles, because their grout flush installation process practically eliminated the risk of creating a pathway for artesian piping. Although not specifically the intent of the micropile design, the soil knitting effect from so many closely spaced, positively bonded elements further reduced the overall risk of foundation performance. More than any of these beneficial aspects of the proposed micropile alternative, total cost and cost certainty – with the risk of soil conditions and pile performance transferred to the piling subcontractor – were the factors that eventually swayed the owner. Once the cost implications were evaluated and compared to the various and several risks associated with the tendered driven pile scheme, the owner was quick to accept the credit offered by the general contractor and approved the change to micropiles.

As part of the change to micropiles, responsibility for design of the piles and the various pile arrangements – calculations demonstrating that the lateral and vertical resistance from the various pile groups were sufficient to adequately support their respective structures – switched from the owner to the general contractor. Despite the fact that the micropile alternate involved installation of more piles relative to the tendered arrangement, care was still taken to ensure that the new scheme did not necessitate any changes to the tendered pile cap design. Due to time constraints, the micropile engineering work was completed on a progress basis: although individual micropile design was proved by pre-production load testing, the engineering of the Centre Pier and West Abutment pile arrangements were still on the drawing table when micropile production installation started at the East Abutment.

**MICROPILE DESIGN CONSIDERATIONS**

Far more than any other single aspect of this project, the need to limit the embedment depth of the micropiles to avoid puncturing into the aquifer was the governing micropile design criterion. This aspect alone meant that each micropile would have to resist substantially smaller loading than each tendered driven pile, but for obvious practical and economic reasons, the depth limitation criterion had to be mollified without causing the pile quantity to explode. Consequently, the design required a micropile type and installation process that would result in the highest pile-to-soil load transfer rate achievable.

Grout flush installation process was selected as the best means of achieving the high pile-to-soil load transfer performance required. The piling subcontractor enjoyed the benefit of having installed several dozen past projects using grout flushed elements. Some of the subcontractor’s past load tests in similar soil proved working adhesions as high as 80 kN/m, but mindful of the risks involved, 65 kN/m was selected as the design load transfer rate. In order to economize by limiting the majority of the installations to consumption of just two bars and one coupling per micropile (i.e. embedment depth = 5.6 metres), individual micropile service loading was subsequently capped at 360 kN. Selection of 360 kN service loading meshed well with the criterion for keeping the pile quantity in check; working with this number in mind, the various micropile arrangements were designed to accommodate the needs of their respective structures, and the result was a reasonable 60% increase in pile quantity relative to the tendered scheme. Selecting 65 kN/m was a calculated risk: the piling subcontractor had to push this number as high as was manageable in order to limit pile quantity, all the while understanding that the assumed adhesion would remain subject to being proven by load testing right up until the very moment when production micropile installation was due to commence. Since the usual fix for a failed load test on a soil-only pile is to lengthen the bond zone – obviously not an option for this project – a failed load test would translate directly into significantly higher pile quantity, entirely at the piling subcontractor’s own expense.

Having determined that 360 kN would be the maximum allowable individual micropile service compression load, the various pile arrangements, under each of the seven piled structures, were designed using both vertical and battered micropiles. All vertical micropiles were designed for axial service loading 360 kN; the battered micropiles were divided into short (5.6m embedment) battered micropiles of axial service load 245 kN and long (7.1m embedment) battered micropiles of axial service loading 360 kN. Lateral loads acting at the bases of the structures were resisted solely by
axial resistance from battered micropiles. In total, 357 micropiles were installed in place of the tendered scheme’s 223 driven tube piles.

In order to prevent reducing the micropile bond zone any further beyond its already short length, the usual practice of adding a concentric upper casing to each micropile was not adopted. Consequently, selection of the sizing of the primary reinforcing member was predicated on finding a hollow bar system strong enough to carry the majority of the micropile design load by itself. The Ischebek Titan 52/26 system ($P_y = 730$ kN; $A_s = 1339$ mm$^2$) was chosen for this reason. The 115mm cross cut bit was selected as the largest catalogue size of Titan 52 drill bit suitable for drilling through the cobble-inclusive layers anticipated. Grout consisted of neat, normal Portland cement at water-to-cement ratio of 0.4, by weight, at design strength 35 MPa. Figure 4 illustrates a typical micropile section and details.

![FIGURE 4: TYPICAL MICROPILE SECTION AND DETAILS](image)

Corrosion protection requirements were satisfied by considering the 120-year loss of steel cross section: the area of steel considered in the axial strength calculation was reduced by 14% (to $P'_y = 628$ kN) as a conservative estimate of the worst effects of corrosion after 120 years. Given the high quantity of piles, it was deemed economically infeasible to adopt the most conservative design approach of only considering the steel section as contributing to the design strength of the micropile. However, the traditional means of assuring full grout section over the uppermost reaches of the micropile – installation of a supplemental upper casing – had already been ruled out. The design approach sought to find a balance between these two opposing concerns. The eventual compromise – taking only 64 kN from an otherwise allowable 127 kN – was reached by conceding that the presence of a mudslab, placed prior to any micropile installation, would take on one of the roles of the missing casing in guaranteeing encapsulation of the micropile reinforcement with an intact cross section of full strength grout over the upper reaches of micropile.
INSTALLATION METHOD

The micropiles were installed using the grout flush, or continuous grout flush, process. True to form of all micropiles, grout flushed micropiles are replacement-type 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 target depth is achieved – thereafter 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. This continuous grout injection results in excellent grout-to-ground adhesion by two actions. First, the soil that is mechanically cut by the rotating drill bit is flushed out of the hole and 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 hole wall and permeation (to the extent possible) of 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.

For this project, top hammer percussive drilling, using a Klemm KD-204 drifter with a hammer energy of 277 Joules per blow, hitting at a rate of 2600 blows per minute and rotating at 145 rpm, enabled trouble-free micropile installation through all soils encountered, including the harder till layers rich in cobbles and boulders. Cement slurry of water to cement ratio of 0.7(by weight) was used as the flushing medium during advance to target depth. Upon reaching target depth, thicker grout of w/c 0.4 was injected until this thicker grout filled the annular space over the entire depth of micropile.

Even though percussive drilling was used, adjacent micropiles were installed without restriction as to the freshness of nearby installations. With 357 micropiles to install and such an aggressive schedule to meet, it would have been impractical to follow conventional proximity/freshness restrictions, and this concession was ungrudgingly granted by the micropile designers in the knowledge that rapid attenuation of energy takes place within minimal radial distance from the tip of the pile, and further that the fluid grout column acts to dampen transfer of installation energy into the soil mass. With this very concession in mind, the designers were careful to ensure that the pre-production test micropiles were installed in this very manner – with adjacent installations proceeding with fresh grout nearby – in order for the load testing to additionally prove this installation-related aspect of the micropile design.

LOAD TESTING

Five different load tests were performed – two sacrificial, pre-production load tests and three proof tests. Typical magnitude of applied test loading was 200% of compression design load (i.e. 2 x 360 kN = 720 kN applied load). The locations of the load tests were spread across the three bridge foundations – 2 tests at the east abutment, 1 test at the centre pier and 2 tests at the west abutment.

Pre-production load testing consisted of one static compression load test on a vertical micropile and one static tension load test on a battered micropile. Both pre-production test piles were embedded in soil immediately outside the footprint of the east abutment foundation. The pre-production load tests sought to verify three design assumptions:

i) The assumed service grout-to-ground adhesion of 65 kN per lineal metre of embedment would suffice to provide a factor of safety with respect to micropile capacity of at least 2.0

ii) Micropile stiffness would suffice to limit the gross pile head deflection to less than 6 mm at design load

iii) Short battered micropiles could be relied upon to exhibit axial performance similar to that of vertical piles

The first pre-production load test was a static compressive load test conducted in conformance with ASTM D1143. Loads were applied cyclically in increments of 25% of design load. The duration of the test was 30 hours, 20 minutes, which included 12 hours held at 200%. The results of this load test confirmed the first 2 of 3 design assumptions.

The second pre-production load test was a static tension test, performed by applying cycled loading in increments of 25% of design load, with 10 minute holds at intermediate test loads (e.g. 25%, 50%, 75%, 125%, etc.) Test loading was held for 60 minutes at 100% and 200% of design load. The results of this load test confirmed all three design assumptions with the added benefit that there could not possibly have been any contribution to micropile axial performance from end bearing resistance, as there may have been during the sacrificial compressive test, given the very short micropile embedment depths.
Three proof tests were conducted: one compression test on a vertical micropile at the centre pier, one compression test on a vertical micropile at the west abutment and one tension test on a battered micropile at the west abutment. A plot of the applied load versus displacement is shown in Figure 5 for the first static compressive proof test, performed at the centre pier.

The compressive proof tests employed production micropiles as reaction anchors (two per load test) (Figure 6). Care was taken in every load test to isolate the micropile reinforcement from the mudslab in order to avoid any false contribution to test pile performance.
Table 1.0 summarizes the performance measured at each of the load tested micropiles.

### TABLE 1.0: SUMMARY OF MICROPILE LOAD TEST RESULTS

<table>
<thead>
<tr>
<th>TYPE OF LOAD TEST</th>
<th>LOCATION</th>
<th>MICROPILE ALIGNMENT (Degrees)</th>
<th>TEST LOAD (kN)</th>
<th>% of Design Load</th>
<th>HOLD TIME @ TEST LOAD (hrs.)</th>
<th>CREEP (6 to 60 mins @ P_test)</th>
<th>GROSS MOVEMENT @ 1.0 DL (mm)</th>
<th>GROSS MOVEMENT @ P-test (mm)</th>
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**DISCUSSION**

In hindsight, it seems obvious that this would have been an ideal project to go to tender on micropiles, but given the chance to do it all over again, the owner would very likely send this job to tender no differently. Micropiles constructed as a value-added alternative were certainly far more cost effective than any prescribed micropile scheme could possibly have been, because a prescriptive micropile design would have to have been so necessarily conservative in its approach as to make it either inconstructible or infeasible. For example, it is highly unlikely that any prescriptive micropile solution based on the grout-flush installation method would assume a service grout-to-ground adhesion any higher than 40 kN/m. Maintaining the maximum micropile embedment depth of 5.7m to avoid penetrating the aquifer, the maximum axial service load would thus be restricted to 230 kN. On this basis, the quantity of individual micropiles would be more than double the quantity of tendered driven piles. This aspect alone would be enough to rule out a prescriptive micropile design approach as a possibility even before considering the allocation of risk. For this project, it took the aggressive design approach of an experienced specialist micropile contractor, willing to accept design and performance related risk and not bound by layers of redundancies designed to protect the owner from the contracting public at large, to conceive and execute a solution that was both constructible and cost effective.

The indirect route by which micropiles were procured as the deep foundations for this project is itself exemplary of the continuing struggle for micropiles to gain traction in the Ontario transportation infrastructure market. More than a decade after publication of the seminal USFHWA micropile implementation manual, there are still only a small handful of qualified micropile vendors in the local marketplace. This is due mainly to the fact that the local foundation drilling community consists primarily of established companies whose equipment, experience and culture make them averse to the risks inherent in gearing up for what is to them a fundamentally different foundation specialty. The very same lack of appetite for this innovative technology applies to the vast majority of the local engineering community, for the very same reasons. The odds remain stacked against the near term prospects for micropiles in the local transportation infrastructure sector, because without these two groups on board, owners for the most part continue to remain blind to the possibilities. Although local outreach efforts continue, both at the grassroots level and through the
auspices of groups like ISM and ADSC, the best hope for micropiles gaining further traction in the Ontario market remains the successful construction of projects such as CPR Morningside.

The Ontario transportation infrastructure market is by far the largest untapped market ripe for penetration by micropiles. The principal owners – the Ontario Ministry of Transport, the Toronto Transit Commission, CN Rail and CP Rail – although slowly coming around to understanding that consideration of micropiles for future projects might be in their own best interests, remain conservative in their foundation design and procurement methods. The example of micropiles at the CPR Morningside Grade Separation project might prove a model for these entities: going to tender based on a market-ready, conventional foundation prescription, but empowering proponents with a stated willingness to entertain value-based, specialty alternatives such as contractor-designed micropiles.

CONCLUSIONS

Micropiles with short embedment depths were unequivocally demonstrated to be well suited to the soil types that underlie the structures at this site. Multiple load tests proved that micropile performance, both in terms of stiffness and capacity, was more than sufficient to meet the needs of the structures being supported. Piles with stiffness derived from bonding into soil rather than structurally via bulk of steel cross section provided this project with a means of overcoming the access and depth restrictions that might otherwise have rendered it inconstructible. This project is a clear demonstration of the applicability of innovative drilling and grouting methods in solving unique geostructural challenges.

The owner and general contractor both benefited from this project being constructed on micropiles in place of the tendered driven piles, because the switch to micropiles resulted in cost certainty and schedule certainty without any compromise to the objectives of the project. No piling-related extras were claimed, and the piling work, including all of the load testing, was completed swiftly. The small equipment used to install the micropiles proved just the tonic for the tight confines of the site. Selection of off-the-shelf materials enabled a fast start to pile construction, and even though only a single drill rig was used, the rate of micropile installation (average 20 installed per shift) was sufficiently brisk to stay apace and even ahead of other concurrent works. Railway and roadway operations were successfully maintained throughout micropile installation.

Although micropiles were not given any true consideration by the owner until they were proposed after tender award, acceptance of micropiles enabled the owner to transfer substantial risk to the piling subcontractor. Furthermore, the fact that micropiles were constructed as a contractor-proposed alternate – based on the contractor’s design and not the owner’s – resulted in the owner’s total foundation cost being less than what would have been paid for either the tendered driven pile scheme or any prescriptive micropile design. Despite these several advantages, the continuing paucity of qualified and willing micropile vendors and micropile designers would likely lead the owner to go to tender no differently if an identical project were sent to procurement today.

REFERENCES


Geo-Foundations Contractors Inc. / Tarra Engineering Inc., 2008, drawings G-08-22 MP1 through MP-5


UK Transportation Research Laboratory, report 380/1993.