Rethinking the Strength Properties of Soils in the Greater Toronto Area

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ABSTRACT
An extensive laboratory testing program was carried out for recent transit expansion projects in the Toronto area. The testing included routine characterization index testing - moisture content, grain size distribution, Atterberg Limits and unit weights - and a suite of advanced testing consisting of approximately 181 triaxial compression test sets (in the order of about 540 specimens) to define the strength properties (friction angle, φ', and the cohesion, c') of the soils for use in design. In this paper, we present a summary of the characterization and triaxial compression results, classified using the physical properties of the TTC Soil Groups.

Two different sampling methods were used to obtain triaxial test samples conventional PQ coring and the faster Sonic coring method. A comparison of the results indicates that the sampling method (PQ or Sonic) had minimal impact on friction angle results, with the Sonic soil samples generally indicating a slightly lower friction angle when compared to those soil samples obtained using PQ methods.

A review of strength parameters recommended for various new developments and transit infrastructure improvement projects was carried out and compared to the results obtained from the triaxial compression testing. Based on this review it appears that geotechnical design engineers may be underestimating the strength of the soils in the Greater Toronto Area favouring to use more conservative values for friction angle and cohesion.

RÉSUMÉ
Un vaste programme d'essais en laboratoire a été réalisé pour les projets récents d'expansion des transports en commun dans la région de Toronto. Les essais comprenaient des essais de routine pour la détermination d'indices de caractérisation - teneur en eau, distribution granulométrique, limites d'Atterberg et poids volumiques - et une série d'essais avancés comprenant environ 181 essais de compression triaxiale (de l'ordre d'environ 540 échantillons) pour déterminer les paramètres de résistance (l'angle de frottement, φ ', et la cohésion, c') des sols à utiliser dans la conception. Dans cet article, nous présentons un résumé des résultats de caractérisation et de compression triaxiale, classés en utilisant les propriétés physiques des groupes de sol de la CTT.

Deux méthodes d'échantillonnage différentes, une avec un carottage PQ conventionnel et l'autre avec un carottage Sonic plus rapide, ont été utilisées pour obtenir des échantillons d'essais triaxiaux. Une comparaison des résultats indique que la méthode d'échantillonnage (PQ ou Sonic) a un impact minimal sur les résultats d'angle de frottement quoique les échantillons de sol obtenus avec le carottage Sonic donnent généralement un angle de frottement légèrement inférieur par rapport aux échantillons de sol obtenus à l'aide du carottage PQ.

Un examen des paramètres de résistance recommandés pour divers projets et développements nouveaux pour l'amélioration des infrastructures de transport en commun a été effectué et comparé aux résultats obtenus à partir des essais de compression triaxiale. Sur la base de cet examen, il semble que les ingénieurs de conception géotechnique sous-estiment la résistance des sols dans la région du Grand Toronto et préfèrent utiliser des valeurs plus prudentes pour l'angle de frottement et la cohésion.

1. INTRODUCTION

Routine laboratory testing, such as moisture content, grain size distribution with or without hydrometer testing, Atterberg Limits and unit weights are commonly carried out to characterize and classify soils, as these are generally quick budget friendly tests. Based on these tests and in conjunction with in situ field testing, typically N-values from the Standard Penetration Tests (and when practical to be carried out in situ Shear Vane Tests), soil properties such as friction angle - φ' and cohesion – c', are selected for design, most often using empirical relationships and the design engineer's experience.

Advanced laboratory testing that would provide an indication of the soil properties, such as triaxial compression and consolidation testing, are carried out on a project specific basis and are generally limited in number (typically 2 or 3 at most), usually as a result of project budget constraints, project schedules or a combination of both. Although the limited number of tests that are carried out to provide some indication of the soil properties, they are generally not statistically significant for designers to consider due to the variability of the results. Consequently, design engineers resort to empirical relationships and experience, obtaining soil properties and parameters based on reference materials such as text books and published papers, which may or may not be relevant to the local conditions and can either underestimate or overestimate the soil properties and parameters. The end result is the use of approximate conservative parameters to provide highly detailed analysis and recommendations on sensitive infrastructure.

Geotechnical investigations for both new and extensions to existing subway infrastructure were undertaken in Toronto by the Toronto Transit Commission (TTC). Given the significant size, scope and risk of these major infrastructure projects, in addition to a full suite of routine characterization laboratory testing, advanced laboratory testing including triaxial compression testing was carried out to better determine and define the strength properties of the soils - friction angle and cohesion. The results of these tests were used to assess various input parameters for finite element/difference analysis.

This paper provides a summary of the routine characterization tests that were conducted and the results and comments on the triaxial compression testing.

2. SITES FOR THE ASSESSMENT

Geotechnical Investigations for a number of transit related projects have recently been undertaken throughout the City of Toronto. Two projects that are the focus of this paper are the Scarborough Subway Extension (SSE) and the Relief Line South (RLS). The general location of each of these alignments is outlined in Figure 1.

Figure 1: Approximate Alignment Locations

2.1 Scarborough Subway Extension

2.1.1 Location and Alignment

The Scarborough Subway Extension is an approximate 6¼km extension of TTCs Line 2 (Bloor-Danforth Line), from its current east terminus at Kennedy Station eastward along Eglinton Avenue East and northward along Danforth Avenue and McCowan Road, to a new terminal station and tail track that was planned between the Scarborough Town Centre Mall and McCowan Road (see Figure 2).

2.1.2 Physiographic Region

Based on the Physiography of Southern Ontario by Chapman and Putman (1984), the subway extension was located in the physiographic region known as the South Slope, which consists of the southern slope of the Oak Ridges Moraine and the southern portion of the Peel Plain. In the Scarborough area, the South Slope primarily consists of the southern portion of the Peel Plain and is described as a rolling glacial till plain with low drumlins and flutings oriented in a northwest-southeast direction.

2.1.3 Subsurface Conditions

The typical subsurface conditions encountered during the geotechnical investigation along the alignment generally consist of a ground surface cover and thin veneer of variable fill overlying an upper glacial till typically comprised of sandy silt/silty sand, clayey silt with seams and local deposits of silt, sand and clay underlain by strata of sands, silty sand/sandy silt and silt. Layers and lenses of coarse sand/coarse sand with gravel were encountered within the sand, silty sand/sandy silt and silt towards the northern limit of the alignment south of Highway 401. Below the non-cohesive stratum, cohesive silty clay and clay with varying amounts of sand were encountered, which were underlain by a lower glacial till comprised of silty clay/clayey silt glacial till. A lower stratum of sand and silty sand/sandy silt was encountered below the lower cohesive till to the south and below the silty clay towards the northern portion of the alignment.

Figure 2: Scarborough Alignment Detailed Location

2.2 Relief Line South (RLS)

2.2.1 Location and Alignment

The proposed RLS was to start at TTCs existing Osgoode Station at University Avenue and Queen Street

West., continue eastward along Queen Street (from John Street to Parliament Street), turning southerly to approximately follow Eastern Avenue, then turning north onto Carlaw Avenue and Pape Avenue, terminating just north of Pape Station on Line 2. The alignment is shown in Figure 3. The project alignment has been change and no longer under design by TTC.

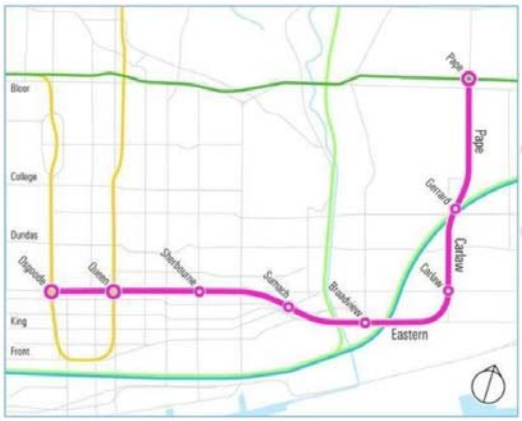


Figure 3: Relief Line South Detailed Alignment

2.2.2 Physiographic Region

Based on The Physiography of Southern Ontario (Chapman and Putnam, 1984) and OGS Earth, the alignment lies within the minor physiographic region known as the Iroquois Sand Plain, which is located within the major physiographic region of the Great Lakes - West St. Lawrence Lowland. The alignment crosses a Bevelled Till Plain in the downtown core and Beach deposits at Danforth Avenue.

2.2.3 Subsurface Conditions

The typical subsurface conditions encountered during the geotechnical investigation along the alignment generally consist of a ground surface cover and thin veneer of variable fill overlying cohesive till (sandy silty clay/silty clay with sand) facing laterally with silty clay underlain by shale at the southern portion of the alignment. Thickness of the overburden in the southern portion of the alignment varies from 10 to 15m, while in the northern portion of the alignment the overburden thickness increases to about 40 to 45m . Passing under the Don River the soil profile consists of lacustrine glacial cohesive silt overlying silty clay. North of Queen Street East, the upper portion of the deposits consists of silty sand/sandy silt/non cohesive silt underlying by silty clay. Further north, the soil profile changes to a non-cohesive till overlying silty sand/sandy silt and shale bedrock.

3. SOIL GROUPS

The Geotechnical Investigation Guidelines required the soils to be assessed and then classified into one of 7 distinct groups (for glacial deposits). The groups were established based on a review of approximately 600 grain size distribution and 200 Atterberg limits tests from various transit related sites and projects though the City of Toronto. Table 1 outlines the group numbers along with a brief description of the soils for each group.

Table 1: Group Number and Description

Group Number	Description
G1	Sand with Gravel
G2	Sand
G3N	Non-Cohesive Glacial Till
G3C	Cohesive Glacial Till
G4	Silty Sand
G5	Silt
G6	Silty Clay
G7	Clay and Clayey silt

The groups outlined above do not consider organic, lacustrine, or alluvial soils nor do they consider river deposits or fill materials. Group 3 Glacial Till, was divided into 2 subgroups, cohesive tills noted as 3C and non-cohesive tills noted as 3N.

To group the soils, a suite of routine characterization grain size distribution and Atterberg Limits tests were carried out. A total of 1235 grain size distribution curves and 862 Atterberg limits tests were carried out. Table 2 provides a summary of the total number of tests carried out for both projects by soil group.

Table 2: Laboratory Test Summary

Soil Group	Gradations	Atterberg	Triaxial Compression Sets	Triaxial Compression Specimens
G1	66	-	9	27
G2	203	-	23	69
G3C	146	149	20	60
G3N	190	178	43	129
G4	255	205	21	63
G5C	75	44	9	27
G5N	106	128	19	57
G6	185	149	36	144
G7	9	9	1	3
Total No.	1235	862	181	543

The grain size distribution and Atterberg Limits charts (where applicable) for each soil group are provided on Figures 4 to 19.

The grain size distribution and Atterberg Limits carried out generally fit well with the initial soil group envelopes. Some adjustments were required to Group 5 – Silts, which were sub-divided into cohesive and non-cohesive silts, identified using a C and N, respectively.

Figure 4 - Group 1, Sand with Gravel

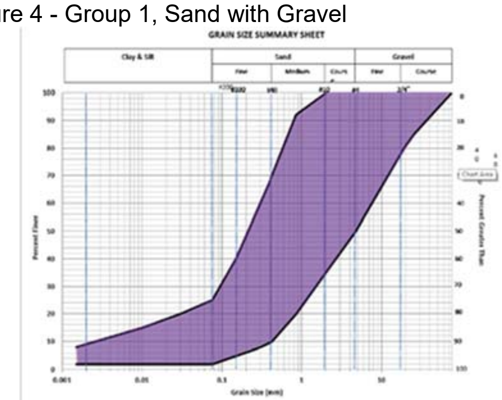


Figure 5 - Group 2, Sand

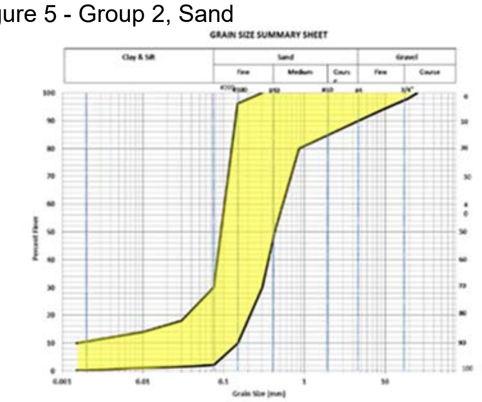


Figure 6 - Group 3N, Non-Cohesive Glacial Till

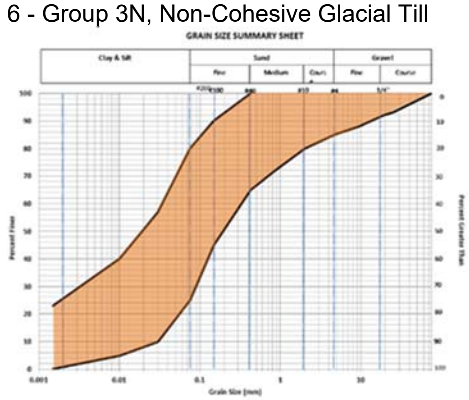


Figure 7- Group 3N, Non-Cohesive Glacial Till

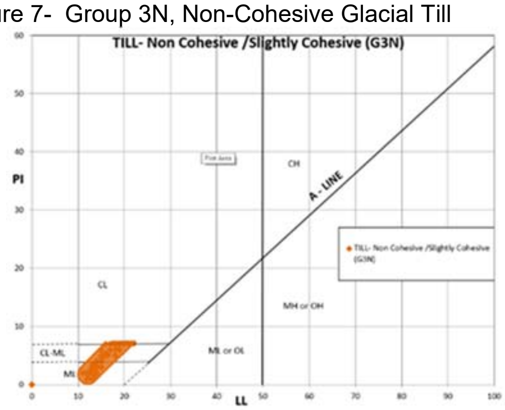


Figure 8 - Group 3C, Cohesive Glacial Till

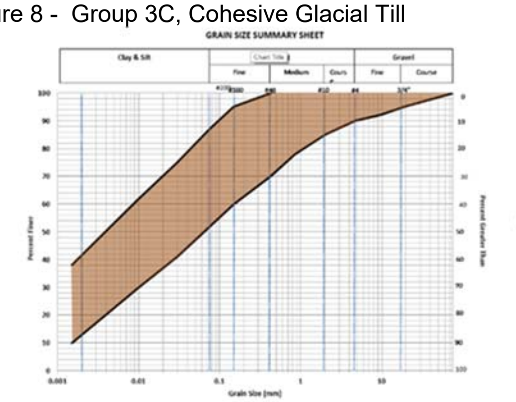


Figure 9 - Group 3C, Cohesive Glacial Till

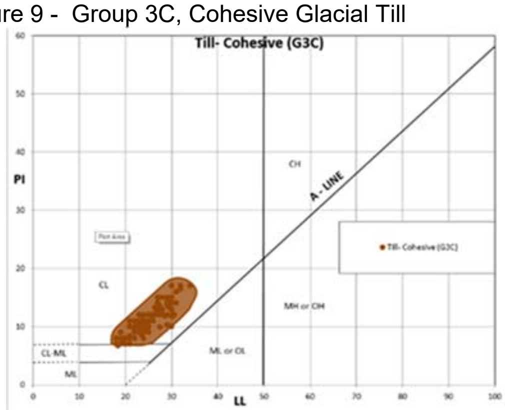


Figure 10 - Group 4, Silty Sand/Sandy Silt

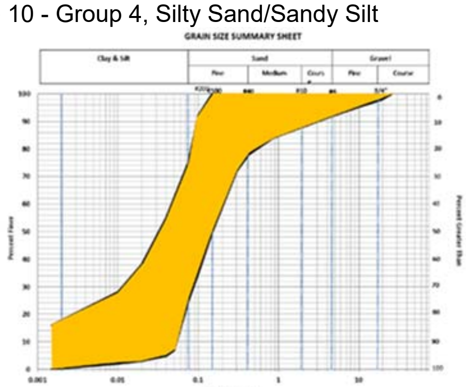


Figure 11 - Group 4, Silty Sand/Sandy Silt

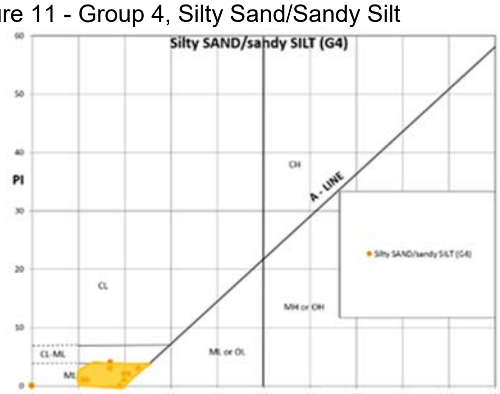


Figure 12 – Group 5C, Cohesive Silt

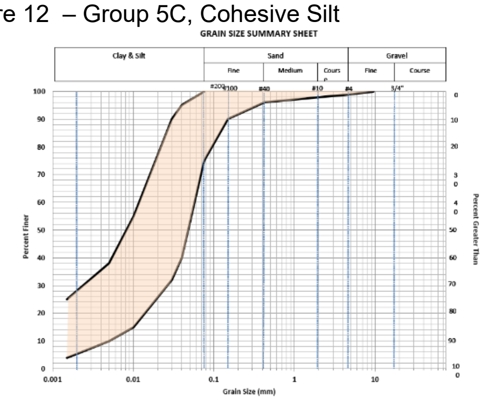


Figure 13 – Group 5C, Cohesive Silt

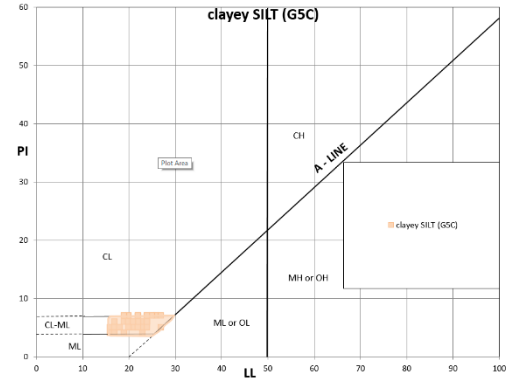


Figure 14 - Group 5N, Non-Cohesive Silt

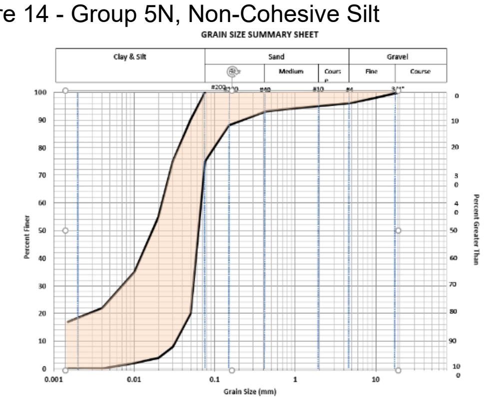


Figure 15 - Group 5N, Non-Cohesive Silt

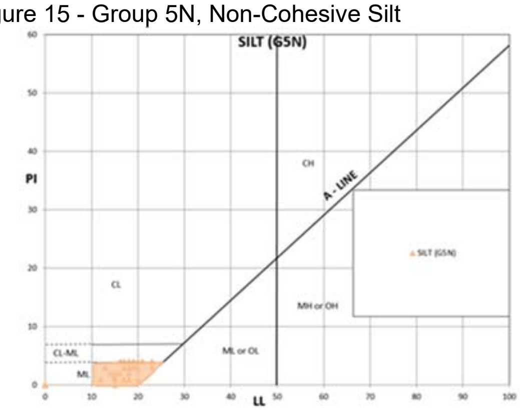


Figure 16 - Group 6, Silty Clay

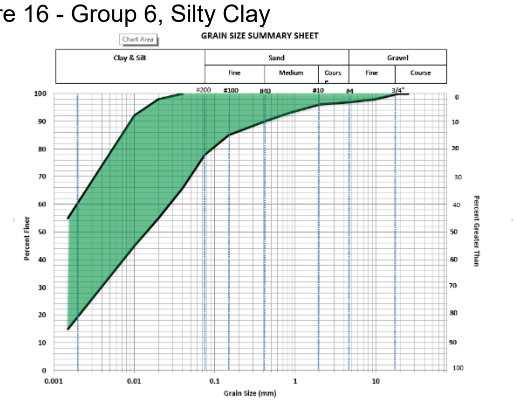


Figure 17 - Group 6, Silty Clay

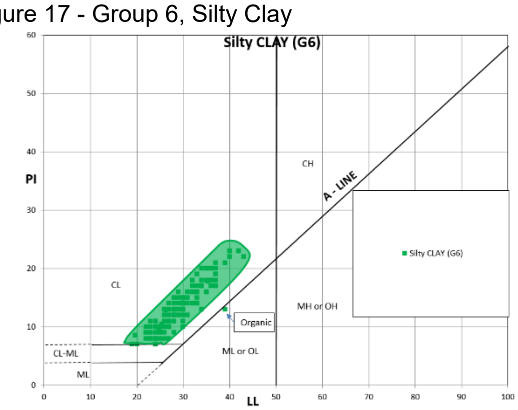


Figure 18 - Group 7, Clay

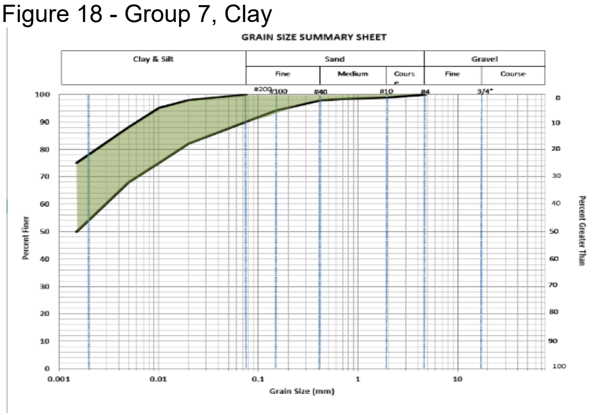
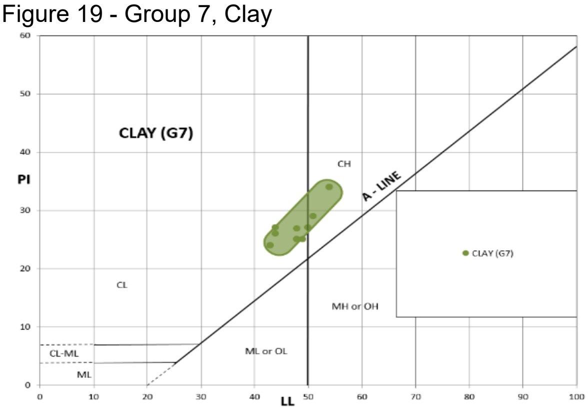


Figure 19 - Group 7, Clay



4. TRIAXIAL COMPRESSION LABORATORY TESTING

A total of 204 triaxial compression sets, approximately 612 individual specimens, were submitted for testing, which consisted of a combination of Consolidated Undrained (CU), Consolidated Undrained Multistage (CUmulti) and Consolidated Drained (CD) compression tests.

181 sets of CD compression tests, approximately 540 specimens, were used for the analysis in this paper. These specimens were associated with the glacial deposits encountered in the Toronto area that all fit well into one of the 7 soil groups. 16 sets carried out using CU and CU multistage compression tests were not considered in the analysis, as soil parameters for computer modeling, such as Eoed_ref, E50_ref, Eur_ref, Poisson ratio, Dilation, co-efficient R and m were required, which can only be assessed from CD tests and not the CU or CU multistage tests.

In addition, eight (8) triaxial compression sets, which were related to alluvial deposits obtained where the RLS alignment crossed the Don River were not considered in the analysis.

A summary of the total number of triaxial compression sets and specimens for both the RLS and SSE projects are provided in Table 2. Given the good agreement with the soil group envelopes, all other lab testing was organized based on the soil group classifications and the total number of sets and specimens for each soil group are also provided in Table 2.

4.1 Analysis and Results

Soil strength parameters, friction angle - φ’ and cohesion – c’, were determined for each triaxial compression set using both the stress path method (q’ vs p’ graphs), and Mohr’s circles.

Friction angle and cohesion summary results specific to the SSE and the RLS are provided in Table 3 and 4, respectively.

Table 3: Summary of Triaxial Compression Test Results, Scarborough Subway Extension

Soil Type	**Summary Table of Parameters (Average)**		**Mohr Circles Summary**		**q' vs. p' Graphs**	
	C' (kPa)	**φ'**	**C' (kPa)**	**φ'**	**C' (kPa)**	**φ'**
G1 Sand with Gravel	5	39°	30	37°	5	39°
G2 Sands	17	42°	55	42°	4	45°
G3C Till - Cohesive	26	34°	55	33°	26	34°
G3N Till - Non-Cohesive	24	40°	55	38°	18	42°
G4 Silty SAND/Sandy SILT	27	42°	40	44°	0	46°
G5 SILT	8	43°	40	42°	0	47°
G6 Silty CLAY	38	33°	50	37°	0	37°
G7 CLAY	18	25°	31	24°	16	26°

Table 4: Summary of Triaxial Compression Test Results, Relief Line South

Soil Type	**Summary Table of Parameters (Average)**		**Mohr Circles Summary**		**q' vs. p' Graphs**	
	C' (kPa)	**φ'**	**C' (kPa)**	**φ'**	**C' (kPa)**	**φ'**
G1 Sand with Gravel	-	-°	-	-°	-	-°
G2 Sands	2	44°	22	44°	13	44°
G3C Till - Cohesive	7	32°	25	32°	9	31°
G3N Till - Non-Cohesive	5	42°	5	42°	3	43°
G4 Silty SAND/Sandy SILT	5	43°	20	45°	0	48°
G5 SILT	1	33°	20	37°	0	37°
G6 Silty CLAY	1.2	31°	20	32°	0	32°
G7 CLAY	-	-°	-	-°	-	-°

A comparison of the results from each line, from different areas of the city, indicate that the strength properties of the soil for both RLS and the SSE are very similar for each soil group, with average friction angles for each soil group varying by about 2 or 3 degrees between sites. There is some variation in the friction angle (2 or 3 degrees) and cohesion (upwards of 40kPa) depending on the analysis method used, stress path or Mohr’s circle.

Given that the results indicate good correlation by soil groups between the site, the data for each soil group from both sites were combined and the results of the stress path analysis for each of the combined results are provided in Figures 20 to 27.

Figure 20 – Group 1, Sand with Gravel

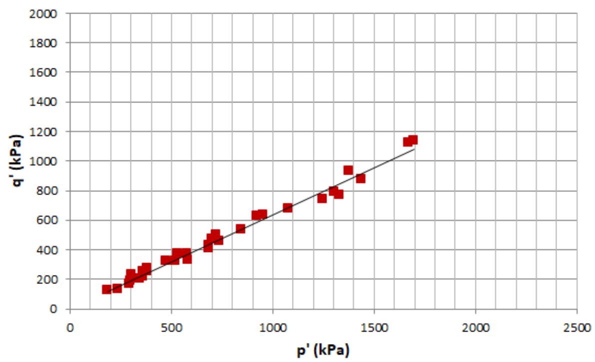


Figure 21 – Group 4, Silty Sandy/Sandy Silt

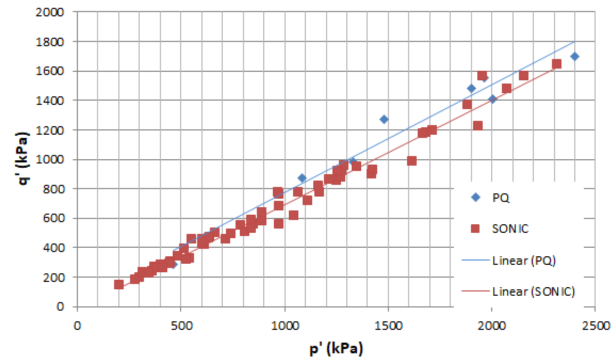


Figure 22 – Group 2, Sand

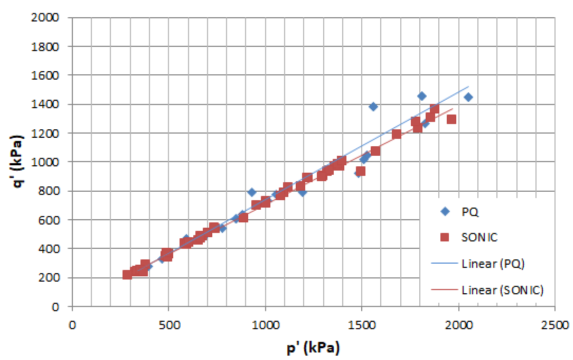


Figure 23 – Group 5C, Cohesive Silt

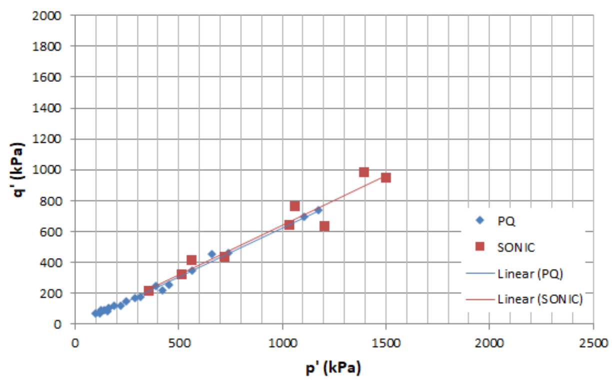


Figure 24 - Group 3N, Non-Cohesive Till

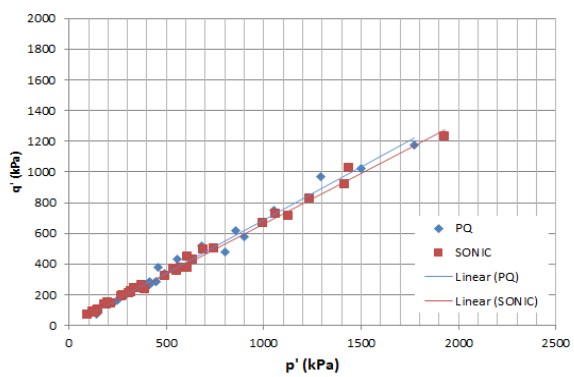


Figure 25 - Group 5N, Non-Cohesive Silt

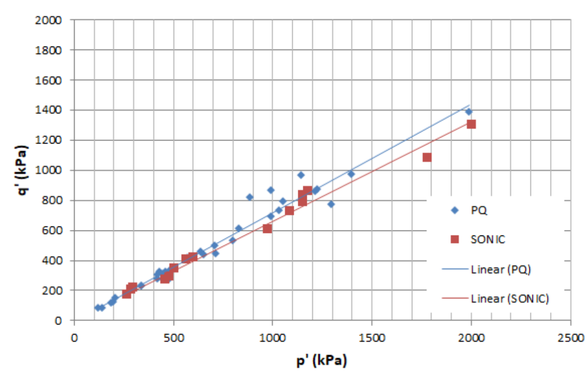


Figure 26 - Group 3C, Cohesive Till

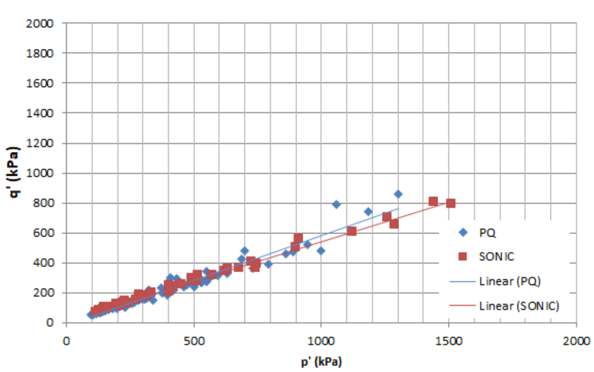
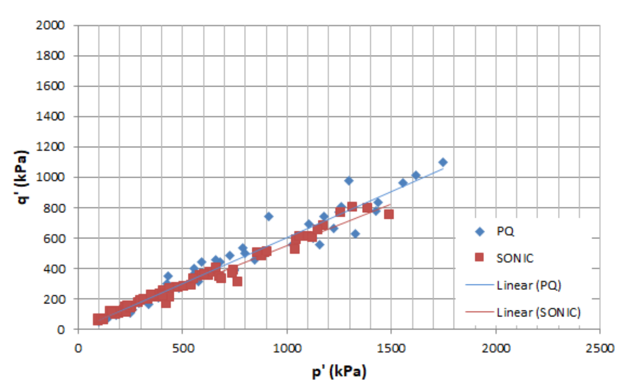


Figure 27- Group 6, Silty Clay



The results of the triaxial testing indicate that the average friction angle for non-cohesive soils (silts, sand and gravels) Groups 1, 2, 3N, 4 and 5N, range from about 40 to 43 degrees with standard deviations in the order of about 3 to 4 degrees. The cohesive soil results including the cohesive glacial till and cohesive silts, Soil Groups 3C, 5C, and 6, range from about 32 to 33 degrees with standard deviations in the order of about 3 to 4.5 degrees. Although the results were provided for soil group 7, clay, it was not considered in the analysis as only 1 triaxial compression set was carried out for this soil group.

Table 5 provides a summary, by soil group, of the average, minimum, maximum and standard deviation for friction angle and cohesion as well as the bulk density and in situ moisture contents for each soil group.

Table 5: Geotechnical Parameter Summary by Group – both Sites

Soil Group	**Parameter**	**Average**	**Minimum**	**Maximum**	**Standard Deviation**
G1 SAND with GRAVEL (compacted)	ϕ', Peak Friction Angle (degrees)	40	35	45	2.9
	C', Peak Cohesion (kPa)	9.9	0	39	14.4
	Bulk Density (kN/m3)	20.2	17.6	22.8	2.5
	Moisture Content (%)	12.3	2.9	28.2	4.2
G2 SANDS	ϕ', Peak Friction Angle (degrees)	43	35.5	46	3.0
	C', Peak Cohesion (kPa)	16.3	0	72	15.9
	Bulk Density (kN/m3)	20.2	16.2	24.0	1.7
	Moisture Content (%)	18.9	2.9	35.6	4.2
G3N TILL - Non Cohesive	ϕ', Peak Friction Angle (degrees)	40	33	46	2.9
	C', Peak Cohesion (kPa)	21.6	0	95	25.0
	Bulk Density (kN/m3)	22.5	17.6	25.6	1.6
	Moisture Content	11.0	2.0	76.9	3.0
G3C TILL - Cohesive	ϕ', Peak Friction Angle (degrees)	32	23	45	2.9
	C', Peak Cohesion (kPa)	13.2	0	78.5	16.3
	Bulk Density (kN/m3)	21.6	21.1	26.8	2.4
	Moisture Content (%)	15.2	3.0	35.0	4.2
G4 Silty Sand/sandy SILT	ϕ', Peak Friction Angle (degrees)	41	33	47	3.9
	C', Peak Cohesion (kPa)	24.0	0	200	40.2
	Bulk Density (kN/m3)	21.1	14.4	25.3	1.7
	Moisture Content (%)	18.0	2.9	35.6	4.2
G5N SILT - Non Cohesive	ϕ', Peak Friction Angle (degrees)	42	29	51	5.2
	C', Peak Cohesion (kPa)	5.8	0	63	14.2
	Bulk Density (kN/m3)	21.6	19.2	27.3	1.37
G5C SILT - Cohesive	ϕ', Peak Friction Angle (degrees)	35	30	44	4.3
	C', Peak Cohesion (kPa)	24.7	0	50	16.5
	Bulk Density (kN/m3)	20.8	19.6	22.8	0.8
G6 Silty Clay	ϕ', Peak Friction Angle (degrees)	33	19	41	4.4
	C', Peak Cohesion (kPa)	30.8	0	125	34.8
	Bulk Density (kN/m3)	20.9	0.0	26.9	2.2
	Moisture Content (%)	20.3	8.0	41.8	3.6
G7 Clay (Single Triaxial Compression Set)	ϕ', Peak Friction Angle (degrees)	25	n/a	n/a	n/a
	C', Peak Cohesion (kPa)	18.0	n/a	n/a	n/a
	Bulk Density (kN/m3)	19.7	18.0	21.8	1.2
	Moisture Content (%)	56.1	25.0	100.0	19.2

5. SAMPLING METHOD COMPARISON

The majority of the samples submitted for advanced testing were obtained using sonic sampling methods, which allowed for quick retrieval of continuous or near continuous soil cores including non-cohesive soils, silts, sands and gravels. Initially the investigations included PQ coring methods to obtain samples for advanced testing but this method generally returned only the cohesive soils, glacial tills and clays, while the silts and sandier soils were washed away with the circulating drilling fluids, which did not happen with the sonic method.

In the early stages of the investigation and given that the quality of the samples obtained using sonic methods appeared to be in very good to excellent condition including the non-cohesive soils, the sonic samples were thought to be good candidates for advanced triaxial compression and consolidation testing. However, there was some concern that the vibrations from the sonic method may have disturbed, either “loosened” or “densified”, the soil samples, leading to test results that may not be representative of the in situ soil conditions. Therefore, samples obtained using both sampling methods were initially selected from the same soil groups and submitted for testing to assess if the sonic sampling method had influenced the soil prior to testing and to what degree the sampling method impacted the test results.

A comparison of the tests early in the investigation indicated there was little difference in the results between the sampling methods. Therefore, sonic sampling was the preferred method for the investigation for the following reasons:

- quicker method and more cost effective - typically about 2 days to complete a 60m long core as opposed to about 5 to 7 days to complete a PQ sampled hole of the same depth;
- quality of the samples that were retrieved; and,
- limited variation in the test results when compared to test results using samples obtained with the more traditional PQ coring methods.

Table 6, provides a comparison summary of the average effective friction angle and cohesion obtained using each test method.

The results indicate that the samples obtained using sonic methods have trend about generally less, by about 1 to 5 degrees, than the results from samples obtained using PQ methods, which in our opinion is within the margin of error, but also errs on the conservative side for design.

However, as previously noted between the two sites, there is some variability in the cohesion between those samples obtained using the sonic and PQ coring methods, with the sonic samples being higher than the PQ samples.

Therefore, the Sonic method was preferred due to the speed with which the samples can be obtained (as previously noted), the quality of the samples and limited variable results compared to PQ samples.

Table 6: Comparison of Triaxial Compression results based on sampling method

Soil Group	PQ		SONIC	
	φ'	c' (kPa)	φ'	c' (kPa)
G1 Sand with Gravel	-	-	40°	0
G2 Sands	46°	1	43°	20
G3C Till-Cohesive	37°	0	32°	15
G3N Till- Non-Cohesive	44°	1	41°	7
G4 Silty SAND/Sandy SILT	47°	61	45°	0
G5N SILT - Non-Cohesive	46°	0	40°	29
G5C SILT - Cohesive	39°	0	40°	0
G6 Silty CLAY	36°	1	33°	4
G7 CLAY	-	-	26°	16

6. DISCUSSION

The results of the triaxial compression testing indicate that the average friction angle for non-cohesive soil groups (silts, sand and gravels) Groups 1, 2, 3N, 4 and 5N, range from about 40 to 43 degrees with standard deviations in the order of about 3 to 4 degrees. The cohesive soil results including the cohesive glacial till and cohesive silts, Soil Groups 3C, 5C, and 6, range from about 32 to 33 degrees with standard deviations in the order of about 3 to 4.5 degrees. Although the results were provided for soil group 7, clay, it was not considered in the analysis as only 1 triaxial compression set was carried out for this soil group.

A review of Published Literature, summarized in Table 7, indicates that the friction angles for non-cohesive soils range from about 28 to 30° to upwards of about 38 to 45°. For cohesive soil the range is in the order of about 20 to 40°, with little information provide regarding cohesion values.

Table 7: Friction angle from literature review (Kulhawy & Mayne, 1990)

SPT N Value	Friction Angle (Degrees)		
	Peck, Hanson, Thornburn - EPRI Manual	**Meyerhoff - EPRI Manual**	**Structural Foundation Designers Manual**
0 to 4	<28	<30	<30
4 to 10	28 to 30	30 to 35	30 to 32
10 to 30	30 to 36	35 to 40	32 of 35
30 to 50	36 to 41	40 to 45	35 to 38
>50	>41	>45	>38

Table 8: Summary and Comparison of Recommended Parameters from Development and Transit Infrastructure Projects and the Triaxial Test Results

Soil Type	Recommended Parameter	Development Reviews			Transit Projects			Triaxial Test Results		
		Min	Max	Average	Min	Max	Average	Min	Max	Average
silty SAND/sandy SILT TILL	Friction Angle deg,	30	38	34	32	36	35	33	46	40
	Cohesion kPa, c'	0	5	1	0	0	0	0	95	21.6
	Unit Weight, kN/m3,	18	27	21.3	20	21	20.8	17.6	25.6	22.5
silty CLAY TILL	Friction Angle deg,	28	36	32	25	36	30	23	45	32
	Cohesion kPa, c'	0	25	7	5	10	7	0	79	13
	Unit Weight, kN/m3,	17	23	21.1	20	23.5	21.4	21.1	26.8	21.6
SAND with silt/silty SAND	Friction Angle deg,	30	40	35	32	38	35	33	47	41
	Cohesion kPa, c'	0	30	3	0	0	0	0	200	24
	Unit Weight, kN/m3,	18	22.6	21.0	19	22	21.0	14.4	25.3	21.1
silty CLAY	Friction Angle deg,	28	38	33	22	33	27	19	41	33
	Cohesion kPa, c'	0	50	21	5	10	8	0	125	31
	Unit Weight, kN/m3,	17	26	21.0	18	22	20.1	0	26.9	20.9

The average values from the test results for non-cohesive soils are at the upper range of those provided in the literature, while the cohesive soils are at the mid range of the limited data with little to no information provided regarding the cohesive value c'.

A review of the friction angle and cohesion values recommended from a number of development review submissions and transit infrastructure improvement projects are summarized in Table 8. Comparing the values recommended by various engineers with the triaxial compression test results indicates that the recommended friction angles of non-cohesive soils are about 5 to 6 degrees less than the tested average values, while the friction angles of cohesive soil are very similar to the tested averages. However, average cohesion, c', is in the order of about 6 to 10 degrees less than the test results and is generally ignored or not recommended for the non-cohesive soils (Although cohesion was measured in the triaxial compression tests it is generally not considered for non-cohesive soils or is termed "apparat" cohesion).

Comparing the triaxial compression test results to the typical published data, the glacial soils in the Toronto area appear to be in the mid to upper end of the ranges that are typically provided in published literature

Based on the above comparison, conservative values for the friction angle of non-cohesive soils and the cohesion value of cohesive materials are being recommended for use in design, which will incorporate some degree of conservatism into geotechnical analyses and design.

7. CONCLUSION

The soil groupings provided a good method to classify the soils and organize the laboratory test results for major infrastructure projects.

There was good agreement of the triaxial compression test results for each soil group between the two sites. However, there was some variation in the cohesion values, which is primarily a result of the method used to analyze the data, Mohr's circles versus stress path, q' vs p' graphs.

The number of triaxial compression sets and specimen tests carried out for each soil group were considered sufficient to provide a good statistical understanding of the soil properties for each site. Given the good agreement of the friction angle results for each soil group between the two sites, the results were combined by soil group to provide a better understanding of the strength parameters.

It is suggested that the characterization laboratory test results may be used to assess the likely strength properties of soils, given the good agreement between the sites based on the soil groups.

The non-cohesive glacial soils in the Toronto area are at the mid to higher end of the ranges that are typically provided in the literature, with friction angle of cohesive soils in the mid range of the limited published values. There is a lack of published compiled data on cohesion in the literature, which likely accounts for conservative recommendations provided for design.

A comparison of the test results to recommendations provided for design by various design engineers for both transit infrastructure projects and development submissions indicates conservative values are being recommended for both friction angle of non-cohesive soils and the cohesion of cohesive soils, while the friction angle recommended for cohesive soils is about the same as the triaxial compression test results.

Based on our review and analysis, lower values for friction angle of non-cohesive soils and cohesion values of cohesive soil are typically recommended for design.

8. FUTURE TESTING

The triaxial compression test results will be used to calculate various soil parameters, such as Eoed_ref, E50_ref, Eur_ref, Poisson ratio, Poisson ratio, Dilation angle and coefficients R and m, in support of finite element/difference computer modeling for various projects in the City of Toronto. The authors are planning to publish the results of their analysis in a subsequent paper.

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