Engineering characteristic of glacial tills in GTA

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GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

ABSTRACT
This paper presents geotechnical investigation results conducted in the glacial till deposits in relation with a light rail transit project in Toronto, Ontario. The ranges of soil parameters including unit weight, water content, strength, modulus, consolidation parameters and shear wave velocity are provided. Statistical analyses of soil parameters are conducted, where available. Possible correlations between SPT N value and pressuremeter modulus and soil friction angle are discussed. In additional, the distribution of boulders and cobbles in the glacial till deposits is also discussed through the observation of a shaft excavation for a tunnel project in Markham, Ontario.

RÉSUMÉ

à Toronto (Ontario). Les paramètres de sol, incluant le poids spécifique, la teneur en eau, la résistance, le module, les paramètres de consolidation et la vitesse des ondes de cisaillement sont fournis. Des analyses statistiques sur les différents paramètres du sol ont été conduites. Des corrélation
pressiomètre sont discutées. De plus, la distribution de graviers est également discutée suite à des observations dans

1 INTRODUCTION

Glacial tills consist largely of unsorted and heterogeneous mixtures of sand, silt, and clay soil particles, with gravel, cobbles, and boulders. Due to the existing of boulders and cobbles, the investigation methods for the glacial tills are limited. The most frequent used in-situ test method is the standard penetration test (SPT) which is a rapid, simple and economical test and widely adopted to assess the properties of glacial tills in the Greater Toronto Area (GTA), Ontario. However, the SPT method often reaches refusal (i.e. blow count N value greater than 50 for 152 mm penetration) when the SPT sampler hits a cobble or boulder within the glacial tills. As the distribution of cobbles or boulders within the glacial tills is random, locally high SPT N values may not be indicative of the relative density or consistency of glacial tills. The apparent soil parameters estimated from such high SPT N values may be overestimated when the sampler hits gravel, cobbles, or boulders or underestimated when the sampler penetrates the soil matrix between cobbles and/or boulders. Milligan (1976) indicated that SPT N-values in excess of 100 blows per 152 mm are not always indicative of extremely high densities, particularly in the case when end bearing piles have been driven into 3.0 to 4.6m (10 to 15 feet) more than the expected depth of refusal in the supposedly dense basal tills.

In order to recognize the real changeability of glacial till properties, a series of laboratory and in-situ testing on the glacial tills have been carried out in relation with a light rail transit (LRT) project in Toronto, Ontario. The laboratory tests include unit weight, moisture content and Atterberg limits measurements, grain size analyses, traxial compression tests, and consolidation tests. The in-situ testing includes SPTs, pre-boring pressuremeter tests and seismic tests. The distribution of boulders and cobbles was examined during a shaft excavation for a tunnel project in Markham, Ontario.

This paper will present the results of laboratory and in-situ tests and shaft excavation conducted in the glacial tills. Statistical analysis of soil parameters including water contents, unit weight, pressuremeter modulus and shear wave velocity are provided. Possible correlations between SPT N value and pressuremeter modulus and soil friction angle are also discussed.

2 REGIONAL GEOLOGY AND SITE CONDITION

The LRT project site is located at Eglinton Avenue in Toronto, Canada. Lake Ontario is approximately 7 km south of the project site. The proposed LRT is approximately 33 km in length from the existing Kennedy subway station in the east to the Pearson International Airport in the west. Due to the surficial congestion in the middle section of the existing Eglinton Avenue, the proposed LRT route includes an underground section with twin tunnels to start from a portal in the west near the Black Creek Drive, cross a well-developed urban area and end at a portal near Brentcliffe Drive in the east. The total alignment length of the twin tunnels is about 10 km.

The existing grade of Eglinton Avenue along the tunneling section, from west to east, varies from about El. 110 m near Black Creek to El. 185 m at the hilltop near Old Forest Hill Road and from this point descends to about El. 105 m near the West Don River.

Based on Karrow (1967) and Sharpe (1980), the GTA experienced at least three glacial and two interglacial periods, during which time a sequence of glacial and interglacial depositions took place. Towards the end of the last ice age, when Wisconsinan glacier withdrew from the Lake Ontario basin to the north and to the east, Lake Iroquois, the forerunner of the present Lake Ontario, was established. The entire sequence of these glacial, interglacial and lacustrine deposits is, however, seldom found intact and usually one or more of these units are absent at any one location. The oldest Quaternary deposits are the Illinoian age represented by the York Till which is overlain by Sangamonian-aged interglacial deposits (sands, silts, and clays) of the Don Formation. The Wisconsinan age is represented by deposits formed during several glacier advances and retreats. Scarborough and Thorncliffe Formations were formed during the glacial retreats, whereas the Sunnybrook Till from the Early Wisconsinan time and Leaside Till (Newmarket Till and Halton Till) from the Late Wisconsinan period were formed during ice advances. Numerical small pockets of lake or pond deposits are found scattered throughout the till plain in depressions at the till surface. These deposits tend to be concentrated along the edges of the major stream valleys.

The bedrock underlying the project site is considered to be the Ordovician age bedrock of the Georgian Bay Formation which consists of typically highly weathered to fresh, grey, very fine to fine grained fissile, weak to medium strong shale with widely spaced jointing and sub-horizontal bedding planes, interbedded with slightly weathered to fresh grey, fine grained strong to extremely strong calcareous siltstone and limestone layers (hard layers). The shaly bedrock formations are subjected to high in-situ horizontal stresses which can impose significant loads on tunnel liner or excavation wall in a time-dependent manner.

3 ENGINEERING PROPERTIES OF GLACIAL TILLS

3.1 Grain Size

Glacial till deposits are distinguished from the interglacial deposits in the textures. The grain size distribution curves of glacial till deposits are generally well graded, consisting of gravel, sand, silt and clay in differential percentages and containing boulders and cobbles. Based on consistency, glacial tills can be divided as cohesionless tills (silty sand till, sand and silt till, and sandy silt till) and cohesive glacial tills (silty clay till and clayey silt till). Due to the nature of deposit and containing clay particle, the cohesionless tills are usually slightly cemented and have a low plasticity to non-plasticity.

Typical grain size analyses conducted on eighteen silty clay till samples taken from the Keele station site showed that the tested samples contain 2% to 11% gravel, 26% to 35% sand, 39% to 48% silt and 18% to 22% clay size particles. The typical grain size distribution curves are presented in Figure 1a.

Consistency (Atterberg) limits tests on the eighteen samples of the silty clay till indicate liquid limits of 20 to 26, plastic limits of 13 to 17 and plasticity indices of 7 to 10, indicating that the silty clay till is low plasticity.

Typical grain size analyses conducted on fifty nine clayey silt till samples taken from the Keele station site

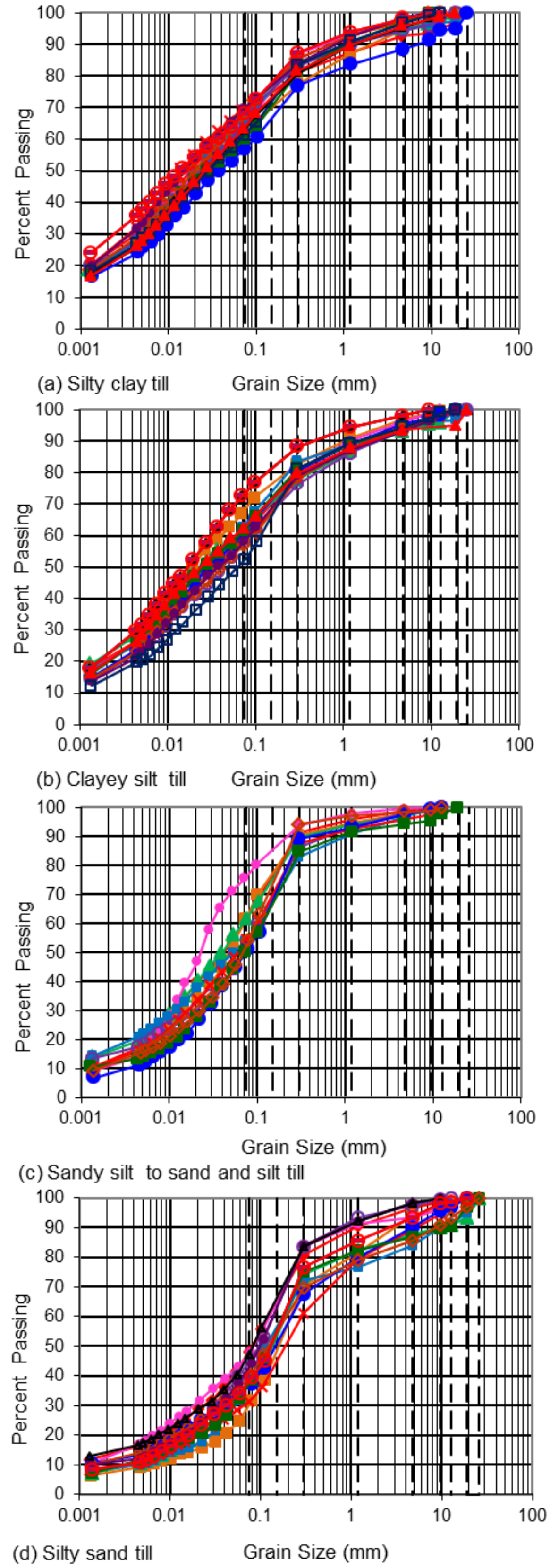

Figure 1. Typical grain size distribution curves of glacial tills

Photograph 1. A boulder taken from a TBM rescue shaft excavation within sand silt till in Markham

Photograph 2. Cobbles taken from a TBM rescue shaft excavation within sand silt till in Markham

showed that the tested samples contain 1% to 10% gravel, 25% to 42% sand, 38% to 53% silt and 13% to 21% clay size particles. The typical grain size distribution curves are presented in Figure 1b.

Consistency (Atterberg) limits tests on sixty samples of the clayey silt till indicate liquid limits of 17 to 22, plastic limits of 12 to 16 and plasticity indices of 4 to 7.

Typical grain size analyses conducted on ten sandy silt to sand and silt till samples taken from the Keele station site showed that the tested samples contain 0% to 4% gravel, 24% to 48% sand, 37% to 66% silt and 8% to 16% clay size particles. The grain size distribution curves are presented in Figure 1c.

Typical grain size analyses conducted on thirteen silty sand till samples taken from the Keele station site showed that the tested samples contain 2% to 16% gravel, 45% to 64% sand, 23% to 37% silt and 7% to 14% clay size particles. The grain size distribution curves are presented in Figure 1d.

Similar grain size distributions for the glacial tills and Atterberg limits for the cohesive tills were also found in other areas in the GTA.

3.2 Boulders and Cobbles

The glacial till deposits are glacial derived and contain cobbles and boulders. The size and percentage of boulders and cobbles within the glacial tills are difficult to be quantified by the borehole drilling, however, the frequent grinding of augers during drilling, presence of rock fragments and locally SPT N-values infer that cobbles and boulders are present within the glacial tills.

Estimation of the size and frequency of boulders has been conducted during the construction of the Sheppard Subway Line (Boone et al. 1998), in which boulder was defined as rock fragments with their maximum dimension being equal to or greater than 300mm. It should be noted that this definition is different from that defined in ASTM (2011), in which the boulders are defined as rock fragments that cannot pass through a screen with 300 mm square openings. Boone et al. (1998) used two parameters to describe the boulder frequency: the boulder volume ratio (BVR), defined as the ratio of the cumulative volume of all boulders to the total excavated volume of ground, and the boulder number ratio (BNR), defined as the number of boulder per cubic metre of cumulative boulder volume encountered. The average BVR and BNR data for the Sheppard Subway Line proposed by Boone et al. (1998) were 0.22% and 11.3, respectively, which led the average boulder volume to be 0.088 m^3. However, Pool et al. (2002) noted 67% of boulders with their volumes less than 0.05 m^3 based on the actual field observation during the construction of the Sheppard Subway Line. This means that the boulder number estimated from the BVR and BNR may be significantly underestimated.

For a tunnel project in Markham, Ontario, the percentage of cobbles and boulders within the sandy silt till was determined from a tunnel boring machine (TBM) rescue shaft excavation, in which 666 cobbles and 3 boulders in 42 m^3 of sandy silt till were recorded. The boulder is defined as a rock fragment with greater than or equal to a volume of a 300 mm diameter equivalent sphere, and the cobble is defined as a rock fragment that cannot pass through a screen with 75 mm square openings and its volume is less than a 300 mm diameter equivalent sphere. Photographs 1 and 2 shows the boulder and cobbles taken for the shaft excavation. If the boulders are defined as rock fragments that cannot pass through a screen with 300 mm square openings as pre ASTM (2011), no boulder was encountered in the shaft excavation. If boulders are defined as rock fragments with their maximum dimension being equal to or greater than 300mm, 5 boulders were encountered in 42 m^3 of sandy silt till. The corresponding value of BVR was 0.18% and the BNR was 67. The BVR value is similar to that found in the Sheppard Subway Line, whereas the BNR is significantly higher than that encountered in the Sheppard Subway Line. This means that the BNR may not be a good parameter to estimate the boulder number in the glacial tills as its value significantly varies from site to site.

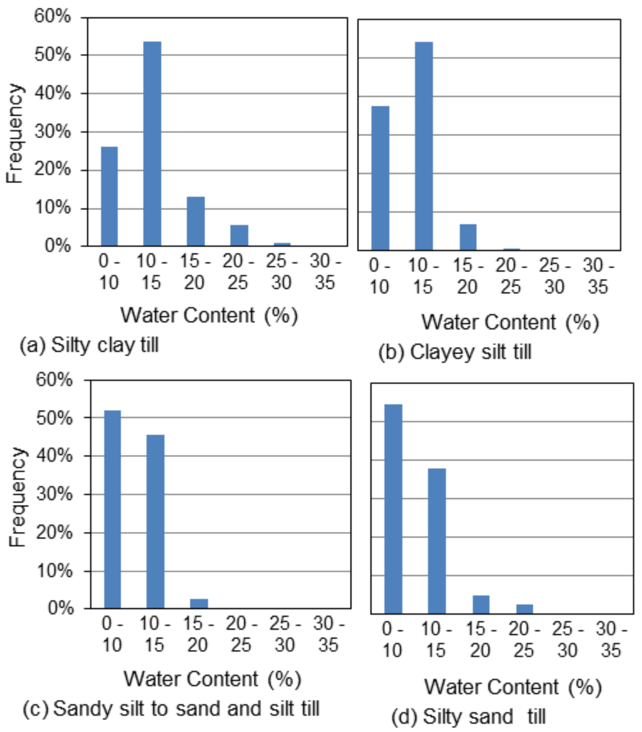

Figure 2. Statistical distributions of water content for glacial tills

3.3 Water Content and Unit Weight

The water content (w) of two hundred and ninety six samples of silty clay till ranged from 7% to 31% with an average value of 13%; and the w of three hundred and sixty seven samples of the clayey silt till was similar with the silty clay till and ranged from 6% to 30% with an average value of 12%.

The w of the sandy silt till to silty sand till is generally lower than that of the cohesive silty clay till to clayey silt till. The w of seventy nine samples of the sandy silt till to sand and silt till ranged from 6% to 20% with an average value of 11%. The w of the silty sand till is similar to that of sandy silt till to sand and silt till, ranging from 7% to 22% with an average value of 11% obtained from seventy nine samples.

Statistical distributions of w of the glacial tills are presented in Figure 2, which indicates that more than 50% of the tested cohesive till samples have the w of 10% to 15%, whereas more than 50% of the cohesionless till samples have the w of 6% to 10%.

The unit weight (γ) obtained from one hundred and nine samples of the silty clay till ranged from 20.0 to 23.9 kN/m^3 with an average value of 22.6 kN/m^3; the γ of the clayey silt till was similar to that of the silty clay till and ranged from 19.9 to 24.0 kN/m^3 with an average value of 22.7 kN/m^3 obtained from one hundred and forty seven samples. Statistical distributions of γ of the silty clay till and clayey silt till are presented in Figure 3, which indicates that more than 50% of the tested clayey silt till to silty clay till samples have the γ of 22.5 to 23.5 kN/m^3.

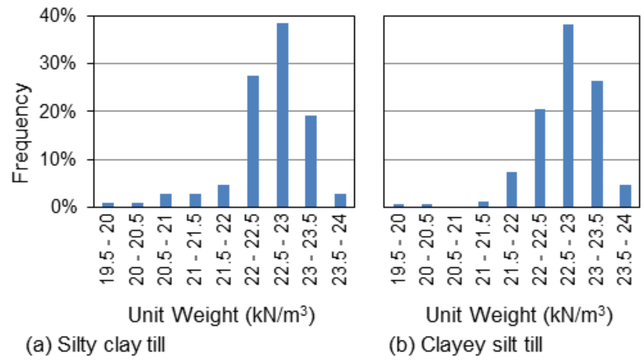

Figure 3. Statistical distributions of unit weight for cohesive tills

The γ of the cohesionless tills are generally higher than that of the cohesive tills. Due to the cohesionless, the unit weight measurement can only be conducted on the samples which show apparent cohesion or cementation. The γ measured from twenty five sandy silt till to silty sand tills ranged from 22.3 to 23.8 kN/m^3 with an average value of 23.2 kN/m^3.

As expected, the unit weights of the cohesive tills decrease with their water contents. Both the silty clay till and clayey silt till show the similar trend as shown in Figure 4. The unit weight of the cohesive tills can be reasonably estimated from the water content using the following relationship:

$$\gamma \text{ (kN/m}^3\text{)} = 24.2 \quad 0.13w \pm 1.5 \qquad [2]$$

The unit weights of the silty clay till and clayey silt till are compared with the SPT N value as shown in Figure 5. It is notes that when the blow number reaches 50, SPT usually stops as it is considered as actually refused and the penetration depth is roughly measured. When SPT N value was greater than 50, the N value was generally calculated from 50 times the ratio of the 305 mm equivalent depth over the measured penetration depth in this paper for the purpose of comparison, i.e. calculated N

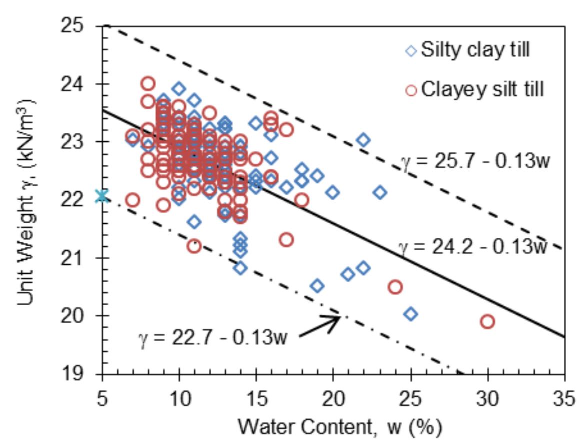

Figure 4. Correlations between w and γ for cohesive tills

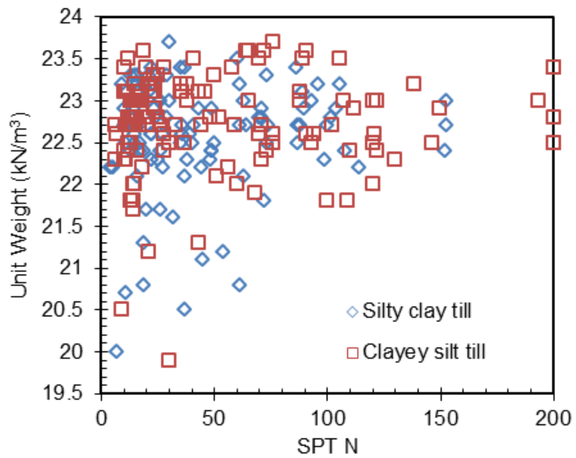

Figure 5. Ccomparison of SPT N with γ for cohesive tills

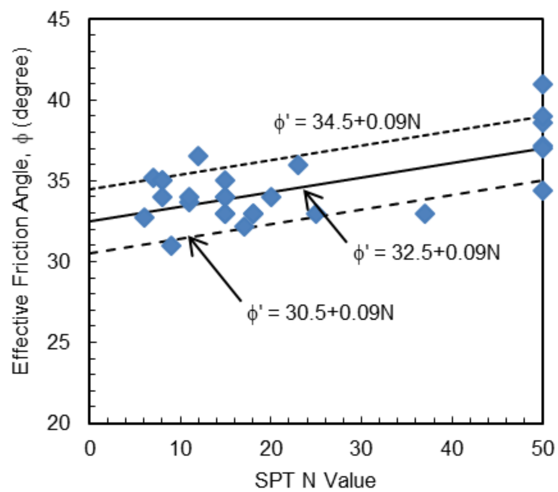

Figure 6. Correlations between SPT N and ϕ for cohesive tills

= recorded N x (305/measured penetration depth in mm). If the calculated N value is greater than 200, the calculated N value is taken as 200. It is clear that there is no correlation between SPT N value and the unit weight for the silty clay till and clayey silt till. However, for higher SPT N values, the unit weight is generally greater than 22 kN/m^3, whereas for the lower SPT N values, the unit weight ranged from 19.9 to 23.6 kN/m^3.

3.4 Strength and Modulus

A series of tests were carried out, which includes triaxial tests, pre-boring TEXAM pressuremeter tests and cross-hole or down-hole seismic tests for the determination of the strength and/or modulus of the glacial tills.

Eighty one (twenty seven series) consolidated undrained triaxial tests on the silty clay till and clayey silt till samples showed the effective angle of internal friction (ϕ ranging from 31^o to 41^o with an average value of 34.5^o

As expected, the ϕ increases with SPT N value as shown in Figure 6, in which SPT N value was taken as 50 when it was greater than 50. The ϕ the cohesive tills can be roughly estimated from SPT N value using the following relationship:

$$\phi \text{ (degree)} = 32.5 + 0.09N \pm 2 \quad [2]$$

Twenty nine pre-boring pressuremeter tests on the silty clay till and clayey silt till showed the pressuremeter modulus (E_{pmt}) ranged from 4.7 MPa to 335.2 MPa with an average value of 87 MPa.

Statistical distributions of E_{pmt} of the cohesive glacial tills are presented in Figure 7, which indicates that there are 38% of the tested cohesive tills with E_{pmt} less than 30 MPa. However, there is also 17% of the tested cohesive tills with E_{pmt} greater than 180 MPa. This could be due to the random distribution of boulders and cobbles within the glacial tills.

The E_{pmt} has be correlated with SPT N value by Cao et al. (2015), who recommended the following relationship for the preliminary estimation of the E_{pmt} in the cohesive glacial tills and glaciolacustrine soils from the SPT N value when the SPT N value is less than 50:

$$E_{pmt} \text{ (MPa)} = 0.9N \quad [3]$$

Similar correlations have also been recommended by Balachandran et al. (2015), who recommended that E_{pmt} (MPa) is about 1.1N.

Figure 8 shows the predicted E_{pmt} values using Equation 3 and the measured E_{pmt} values at the Keele station site. The values of the predicted E_{pmt} are generally close to the measured data.

It should be noted that Equation 3 is only for a rough estimation of pressuremeter modulus from the SPT N value. When the SPT N value is greater than 50, a big error could be induced using Equation 3 and the direct measurement of the modulus is preferred.

Twenty two seismic tests on the silty clay till and clayey silt till showed the shear wave velocity (V_s) ranged from 135 to 520 m/s an average value of 296 m/s. The dynamic shear modulus calculated from the V_s range from 32 to 976 MPa with an average value of 278 MPa.

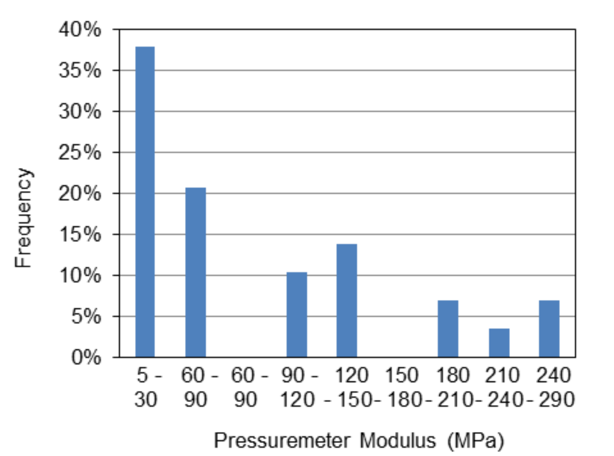

Figure 7. Statistical distributions of pressuremeter modulus for cohesive tills

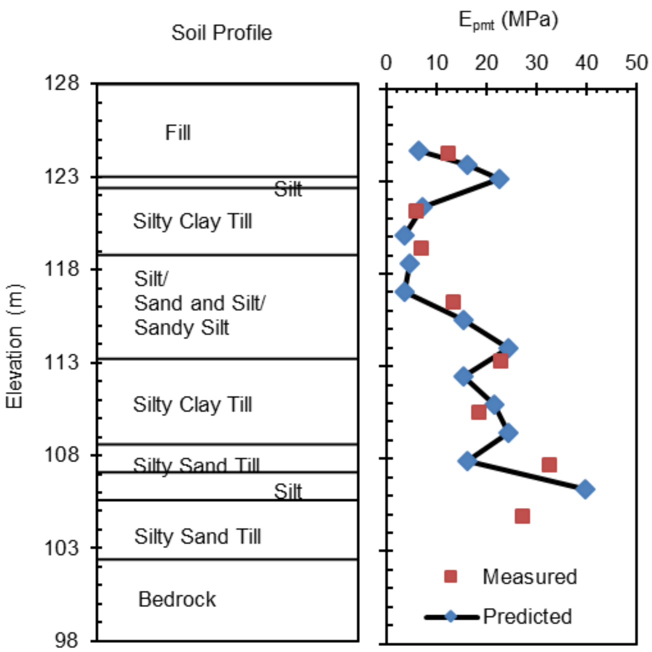

Figure 8. Predicted versus measured E_{pmt} at Keele station site

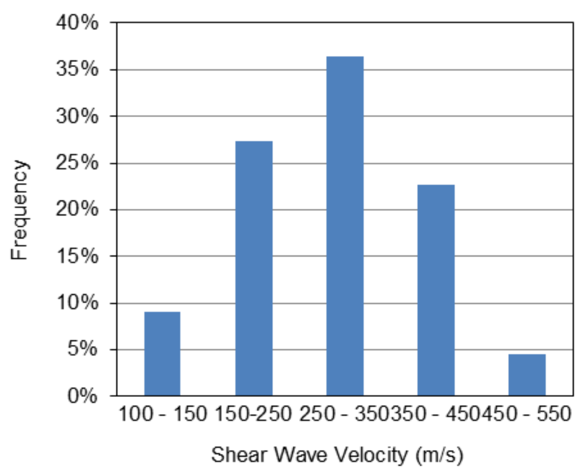

Figure 9. Statistical distributions of shear wave velocity for cohesive tills

Statistical distributions of V_s for the cohesive glacial tills are presented in Figure 9, which indicates that there are 36% of the tested cohesive tills with the V_s of 250 to 350 m/s.

It is found that the dynamic shear modulus calculated from the shear wave velocity is about 5 times the pressuremeter modulus for the cohesive tills.

3.5 Consolidation Parameters of Cohesive Tills

Thirteen oedometer (one dimension consolidation) tests on the cohesive till samples indicated that the cohesive tills are generally overconsolidated. The compression index (C_c) of the clayey silt till and silty clay till ranged from 0.037 to 0.101 with an average value of 0.07 and the recompression index (C_r) ranged from 0.008 to 0.016 with an average value of 0.011. The initial void ratio (e_o) ranged from 0.25 to 0.46 with an average value of 0.36. The coefficient of consolidation (c_v) ranged from $2x10^{-2}$ to $5x10^{-4}$ cm^2/s.

4 CONCLUSIONS

This paper provides the range of soil parameters for the glacial tills with emphasis on the cohesive tills in the GTA. Statistical analyses of soil parameters are provided, where available. The empirical correlation between SPT N value and pressuremeter modulus is discussed. This correlation is useful for the estimation of the modulus when the pressuremeter tests are unavailable for SPT N values less than 50. The empirical correlation between SPT N value and friction angle is also proposed for the rough estimation of the friction angle from SPT N value.

The distribution of boulders and cobbles was examined through the observation in the shaft excavation for a tunnel project in Markham, Ontario. It is found that the variation in the boulder volume ratio may be small from site to site, whereas the boulder number ratio could significantly vary from site to site.

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