Geotechnical Characteristics of Barlow-Ojibway Clay in Northern Ontario

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

Drevininkas, A.
Downunder Geotechnical Limited, Maple, Ontario, Canada
Manzari, M.
Thurber Engineering Limited, Oakville, Ontario, Canada
T. Sangiuliano, D. Staseff
Ministry of Transportation of Ontario, Toronto, Ontario, Canada

ABSTRACT
After the Late Wisconsinan glaciation retreat, the last proglacial lake was formed in northern Ontario and Quebec and is called Lake Barlow-Ojibway. The clay is typically known to be slightly overconsolidated, soft to firm in consistency, with a high compression index. To date a consolidated study based on large scale data in order to provide typical ranges of geotechnical properties and possible correlations for this specific lake deposit has not been conducted.

Hundreds of geotechnical investigations have been carried out within the Lake Barlow-Ojibway clay deposits in northern Ontario by the Ministry of Transportation of Ontario and others since the 1950s. This paper presents a summary of all the testing available to the authors in conjunction with the results from published literature. An analysis of the compiled results is further provided to characterize the compressibility characteristics of the Lake Barlow-Ojibway clays and its correlations with simple geotechnical index properties.

Résumé
Suite au retrait des glaces de la fin du Winconsinien, le dernier lac proglaciaire, nommé Lac Barlow-Ojibway, s'est formé dans le nord de l'Ontario et du Québec. L'argile est connue pour être légèrement sur-consolidée, sensible, de consistance molle à ferme et avoir un indice de compression élevé. À ce jour, une étude de synthèse utilisant des données à grande échelle et ayant comme objectif de fournir une marge de propriétés géotechniques typique et les corrélations possibles pour ces dépôts spécifiques n'a pas été menée.

Des centaines d'études géotechniques ont été réalisées dans les dépôts d'argile du lac Barlow-Ojibway dans le nord de l'Ontario par le Ministère des Transports de l'Ontario et d'autres organismes depuis les années 1950. Cet article présente un résumé de tous les essais à la disposition des auteurs et tous les résultats publiés dans la littérature. De plus, une analyse des résultats compilés permet de donner les caractéristiques de compressibilité des argiles du lac Barlow-Ojibway et ses corrélations avec de simples propriétés d'index géotechniques.

1 INTRODUCTION

Weak clay deposits known as the Clay Belt were formed within the proglacial Lake Barlow-Ojibway in Northern Ontario. Although there are published and well known correlations for low to medium plasticity clays for other clay deposits, reliable correlations for soil properties of medium to high plasticity in this deposit that can be used to predict first order settlement in this deposit are not available. The correlations derived for the low to medium plasticity clays tend to under predict settlements for the loads applied to northern Ontario clays.

The compressibility characteristics of clays are typically determined by obtaining a limited number of relatively undisturbed samples and conducting laboratory oedometer (consolidation) testing to obtain soil parameters. These laboratory tests are expensive and time consuming. Correlation with quick and inexpensive index laboratory test results would provide a more cost effective and efficient method to assist in the prediction of settlements, as well as to calibrate in situ testing methods. Other options include profiling soil parameters for settlement analysis by carrying out in situ testing, such as piezocone penetration testing (CPTu).

2 GEOLOGY

Soft freshwater varved clays were deposited in Glacial Lakes Barlow-Ojibway and Agassiz, which covered much of Northern Ontario between 18,000 and 6,000 years ago during the retreat of the Wisconsin Ice Sheet.

Lake Barlow-Ojibway south of current James Bay existed as a variably sized proglacial lake from about 10,000 to less than 8,000 years ago. During its later stages, it is presumed to have been interconnected with shrunken Lake Agassiz (see Figure 1 and 2).

The large ice-dammed lakes of Northern Ontario, such as Lake Barlow-Ojibway, left vast clay deposits across the Canadian Shield. These formed flat clay belts, such as the Great Clay Belt of the Cochrane District and the Little Clay Belt at the head of Lake Timiskaming.

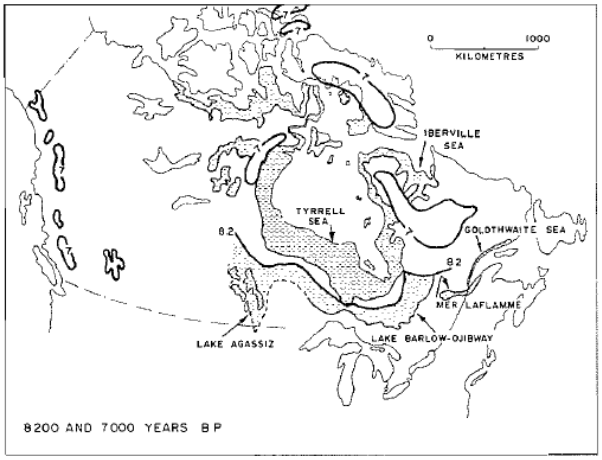

Figure No. 1. Evolution of the major glacial lakes of eastern Canada (Quigley 1980).

The decay of the Laurentide Ice Sheet during the last deglaciation was accompanied by massive release of glacial meltwaters that led to the development of Lake Ojibway and Lake Agassiz over the isostatically depressed terrain of north-central Canada. Lake Ojibway was an important meltwater reservoir that covered large areas in northeastern Ontario and northwestern Quebec. The evolution of Lake Ojibway is closely linked with the behaviour of the southern margin of the Laurentide Ice Sheet, which retreated northward in contact with waters of Lake Ojibway.

Progressive thinning of the Laurentide Ice Sheet margin in the greater James Bay region eventually led to the isolation of the Hudson Bay ice dome to the west and the New Quebec ice dome to the east. As the ice margin receded, the lake expanded northward and caused a large volume of meltwater to be impounded into a relatively closed basin centred over the large topographic low formed by James Bay (Roy et al, 2011).

Lake Ojibway reached a maximum elevation of at least 460 m. For most of its existence, the lake level was controlled by the Kinojevis outlet near the James Bay – St. Lawrence drainage divide and overflow was routed to the St. Lawrence River drainage system through the Ottawa River Valley. Deglaciation was also punctuated by readvances of the Hudson Bay ice into the Ojibway basin, known as the Cochrane surges. These occurred during the final stages of deglaciation which ended with the sudden drainage of Lake Ojibway waters into the Tyrrell Sea waters about 8,000 years ago.

The Cochrane readvance of glacial ice out of James Bay occurred about 8,200 years ago, overriding soft clays for about 250 km south as far as Iroquois Falls. The clay deposit is normally consolidated south of the ice front and overconsolidated north of the ice front. Final retreat of the ice was apparently very rapid because Cochrane till rarely has soft clays overlying it.

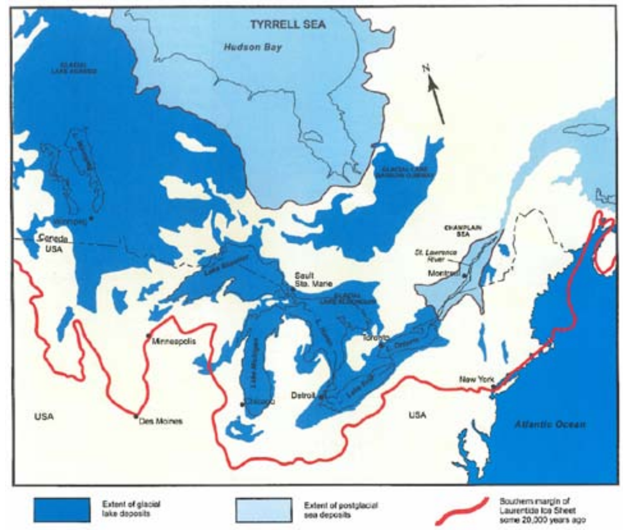

Figure No. 2. Glacial lake deposits (Eyles 2002).

3 DESIGN METHODOLOGY

The thick deposits of varved clays deposited in northern Ontario and Quebec present foundation engineering challenges in the design and construction of highway embankments, bridge structures, dams, tailing ponds and buildings. The performance of these structures depends on an assessment of stability and settlement. This paper focuses on the settlement aspect of embankment and footing performance.

Determination of the compressibility characteristics of the native clay soil is essential to the assessment of the magnitude and time rate of consolidation settlement. The prediction of the magnitude and time rate of consolidation settlement is a function of the preconsolidation pressure, the coefficient of consolidation and the drainage path. In a varved clay, the model of prediction must consider the alternating layers of less permeable cohesive soils and the more permeable silt layers. The varved nature of the clay does not significantly affect the compressibility of the clay but it has significant effect on the drainage path and time rate of settlement.

4 DATA COLLECTION AND ANALYSES

MTO and other consultants have carried out hundreds of geotechnical investigations across Northern Ontario within the Barlow-Ojibway clays since the 1950s for highway embankments, bridge structures, buildings and mining facilities. As part of these geotechnical investigations, soil properties have been determined by laboratory and in situ testing. Geotechnical investigations at fifty-two (52) sites were compiled where oedometer testing was carried out by various geotechnical consulting laboratories or at MTO laboratories. The general locations of the 52 geotechnical investigation sites are presented in Figure 3.

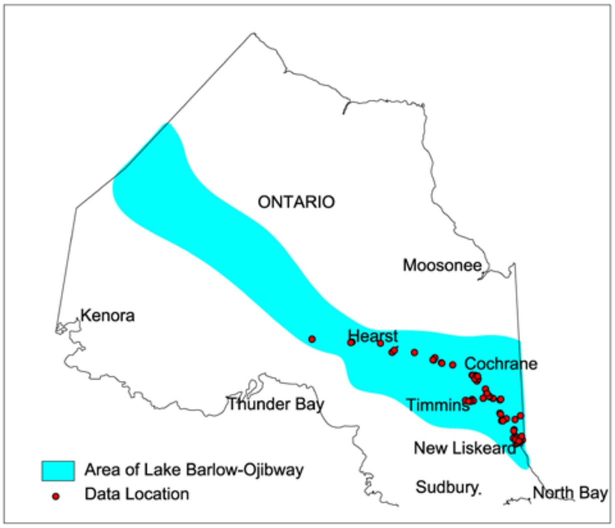

Figure 3. Location of 52 geotechnical investigations.

4.1 Data Collection

The borehole logs and laboratory testing from the 52 sites were analysed and interpreted values for the following geotechnical parameters were obtained:

- Natural moisture content (w_n),
- Initial Void Ratio (e_0),
- Atterberg Limits determinations,
    - Liquid Limit (w_L)
    - Plastic Limit (w_P)
    - Plasticity Index (I_p)
- Overconsolidated Ratio (OCR),
- Preconsolidation Constrained Modulus (M_i),
- Post-consolidation Constrained Modulus (M_P),
- Compression Index (Cc), and
- Recompression Index (Cr).

Over 152 oedometer tests and 128 Atterberg Limits determination tests results were collected for analyses.

4.2 Data Analyses

The procedure for evaluating sample disturbance described by Lunne et al (2006) was used to assess each consolidation test to determine if high quality data was available. A total of 102 excellent to fair quality oedometer tests of the Barlow-Ojibway clays were used in the analysis.

The C_c and M_P values were determined based on the uncorrected consolidation data and not field corrected data as per the Schmertmann method (Schmertmann 1955).

C_r and C_c are the most commonly used parameters for settlement analysis when oedometer test results are available. M in the pre-consolidation stress range (M_i) is typically used when other in situ testing methods (such as CPTu) are carried out for settlement analysis.

The following equation was used to determine M_i and M_P, which is stress dependent and equivalent to the inverse of the coefficient of volume compressibility, m_v, as determined in the consolidation test.

$$M = \Delta\sigma_v' / (\Delta e / (1+e_0)) \quad [1]$$

Where σ_v' is the effective vertical stress. For M_i the change in σ_v' and e were determined for the range of the estimated in situ stress and the interpreted preconsolidation pressure (σ_p'), determined by the Casagrande method (Casagrande 1936). For M_P the range of σ_v' and e were determined from σ_p' to the void ratio at 500 kPa.

The interpreted results from the oedometer tests were compared to each of the geotechnical index laboratory tests in order to assess potential correlations. A regression analysis was carried out to estimate the relationship among the variables. R-squared (R^2) statistical regression analysis was carried out as a measure of how close the data fits to the estimated regression line in order to produce usable correlations.

5 RESULTS

The tests were evaluated to determine suitable correlations between compressibility characteristics of the Barlow-Ojibway clay and routine index properties. The following sections present the results of the evaluation.

5.1 Atterberg Limits

Barlow-Ojibway clay ranges from low to high plasticity, as shown in Figure 4.

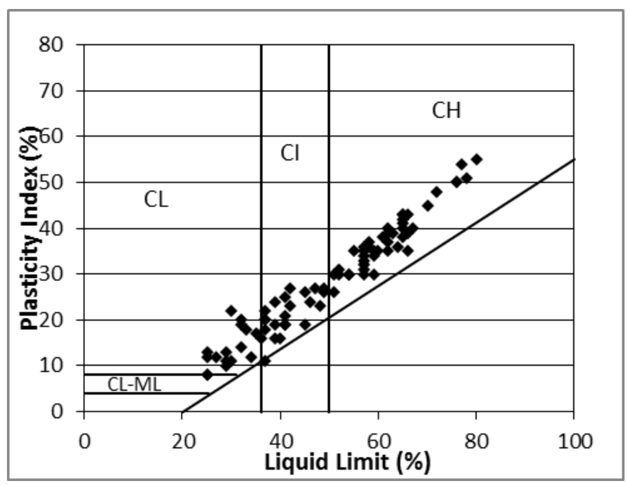

Figure 4. Plasticity Chart for Barlow-Ojibway clay samples

Plasticity parameters (w_L, I_P) with depth did not provide a meaningful trend but there is a general trend with elevation, as noted in Figure 5

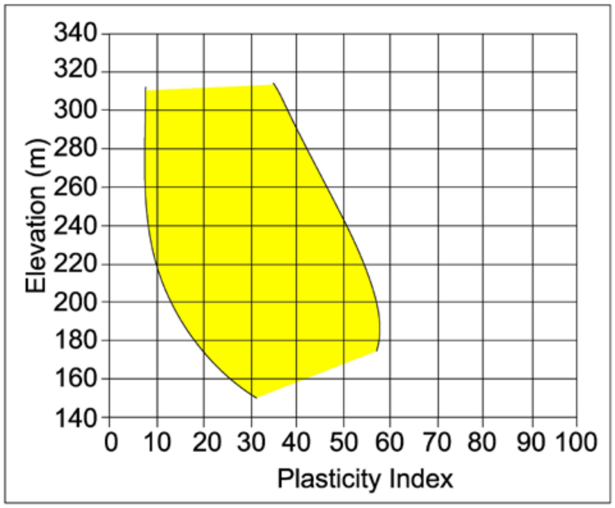

Figure 5. I_p vs. Elevation.

5.2 Preconsolidation Pressure

The apparent σ'_p obtained from oedometer tests versus depth and elevation provided a general trend for the glaciolacustrine clay across all the sites. The σ'_p for the Barlow-Ojibway clay is influenced by both aging process (Bjerrum 1973) and traditional concept of overconsolidation as a result of erosion. Given the influence of aging, the actual magnitude of σ'_p depends on the rate of the applied load. Therefore, the preconsolidation pressure to be experienced in the field during construction of embankments would be different than σ'_p observed from laboratory tests that are shown in Figure 6. A correction factor ranging from 0.9 to 1.1 (depending on OCR) has been proposed for Leda Clays (Morin et al, 1983) to correct the σ'_p obtained from conventional oedometer tests for the field condition. Similar large scale studies of a few real embankment projects should be conducted on Barlow-Ojibway clays in order to assess the correction factors for the rate of construction. Meanwhile, the correction factors provided for Leda Clays or other similar medium to high plastic clays can be used as preliminary values for the Barlow-Ojibway clays as well.

The top layer of the clay has been subjected to desiccation, frost action and weathering. The moisture content is changed and fissures are formed within this affected zone, called the crust. The apparent σ'_p and compressibility characteristic of the clay within the crust is relatively sporadic, compared to the lower intact clay. The σ'_p obtained from the oedometer tests of samples collected from the typical crust (extending to depths of about of 4 m) have been excluded from the assessments provided in this paper. This reduces the oedometer tests used in the assessments to a maximum of 67 tests. The typical range of observed OCR by depth is shown in Figure 7.

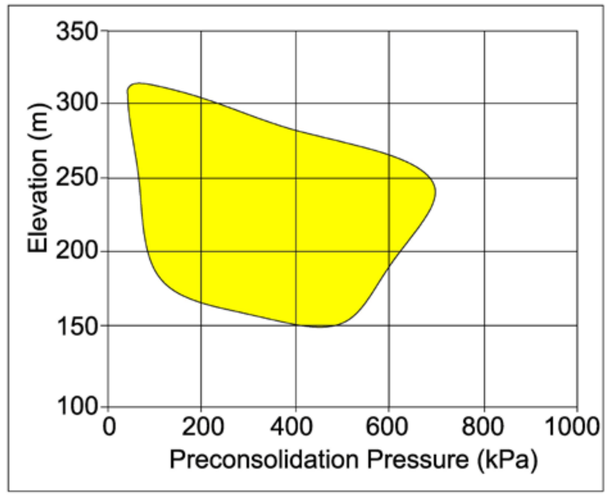

Figure 6. σ'_p vs. Elevation - σ'_p determined by the Casagrande procedure (Casagrande 1936).

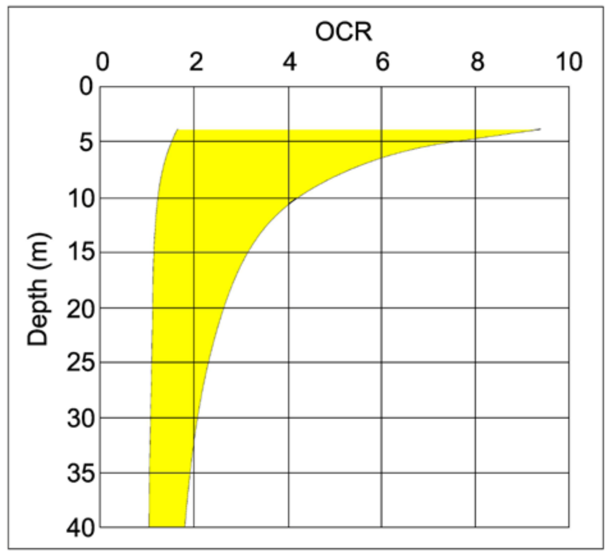

Figure 7. Typical range of OCR vs depth.

In our opinion, the apparent σ'_p of this lake deposit is mostly influenced by the traditional concept of overconsolidation rather than aging. The overconsolidation is a result of erosion and possibly combined with readvance of glaciation. Both these effects can be summarized in the concept of overconsolidation difference (OCD). Assuming a bulk unit weight of 17.5 kN/m^3, Figure 8 presents the inferred erosion which is a combination of the erosion of the lakebed and possible effect of glacial readvance, responsible for the overconsolidation of the clay. Based on our assessment of the data, the lake was ultimately deposited at different elevations. The higher ground surface elevations are associated with the western portion of the deposit in the area of Longlac (current elevation of ±310m), and the lower ground surface elevations are associated with New Liskeard (current elevation of ±180m). The surface of the lakebed was likely as high as elevation 310m to 330m in the western portion of the study area and as high as 190m to 230m in the eastern portion of the study area.

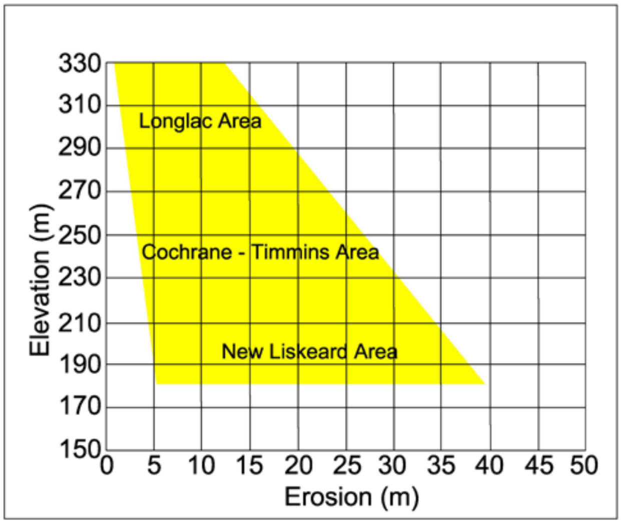

Figure 8. Inferred erosion of lakebed vs ground surface elevation.

5.3 Recompression Index

Recompression Index (C_r) ranged from 0.01 to 0.16 with an average of 0.06 and typically ranged from 0.02 to 0.10. The typical range of C_r with $1+e_0$ is provided in Figure No. 9 and the general correlation is provided below, which has a R^2 of 0.45. Based on the relatively low R^2 value, the correlation between C_r and void ratio is not very strong.

$$C_r = 0.008\ (1+e_0)^{2.363} \qquad [2]$$

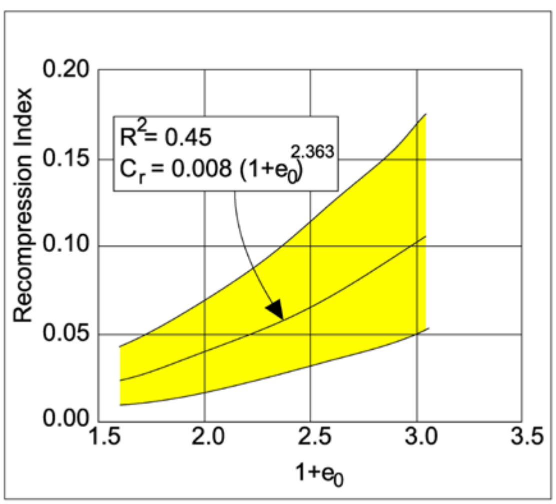

Figure 9. Correlation of Recompression Index vs $1+e_0$.

5.4 Compression Index

Compression Index (C_c) ranged from 0.09 to 2.5 with an average of 0.63. In general, there should be a theoretical direct correlation between void ratio (e_0), water content (w_n), and unit weight (γ) of the saturated soils based on specific gravity (G_s). However, the best correlation between C_c and these index properties (e_0, w_n, γ) were obtained between C_c and $1+e_0$, with a R^2 of 0.81. Figure 10 presents the range of C_c versus $1+e_0$ and the best fit correlation as follows:

$$C_c = 0.023\ (1+e_0)^{3.653} \qquad [3]$$

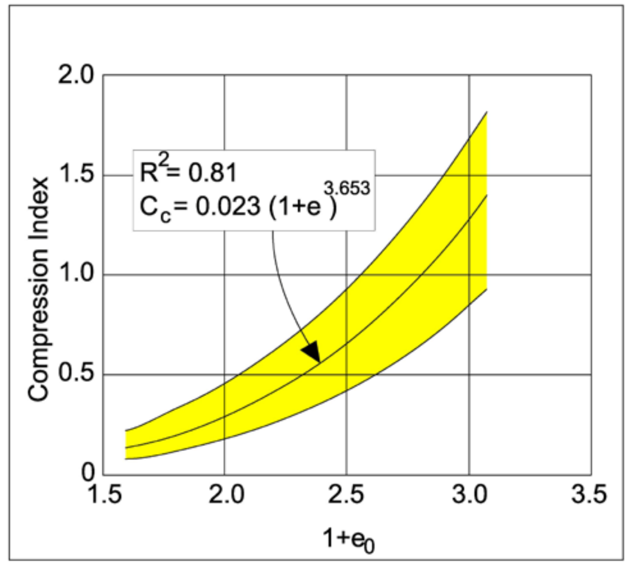

Figure 10. Correlation of C_c vs $1+e_0$ (all tests).

As noted before, although e_0 is dependent on w_n and γ by theory for saturated soils, the correlation between C_c and w_n or C_c and γ was not as consistent as the correlation between C_c and e_0. For reference, Figure 11 presents the range of C_c versus w_n with R^2 of 0.75 which is lower than the R^2 for correlation between C_c and e_0. It should be noted that this correlation is generally equivalent to Equation 3. The discrepancy in the range of values is likely due to the variation of in situ saturation.

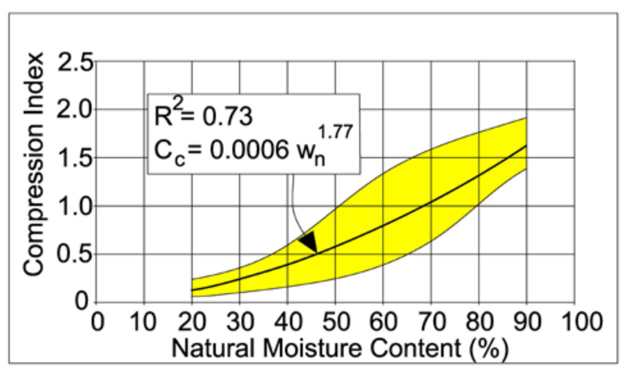

Figure 11. Correlation of C_c vs w_n.

Atterberg Limits determination results were available for 52 of the consolidation tests. Correlation was poor between C_c and w_L with a R^2 of 0.27.

5.5 Preconsolidation Constrained Modulus

In general M_i ranged from 0.6 MPa to 17.8 MPa, with an average of 4.7 MPa for 91 tests, and typically ranged from 0.6 MPa to 8 MPa. The typical distribution range of M_i versus elevation is shown in Figure 12.

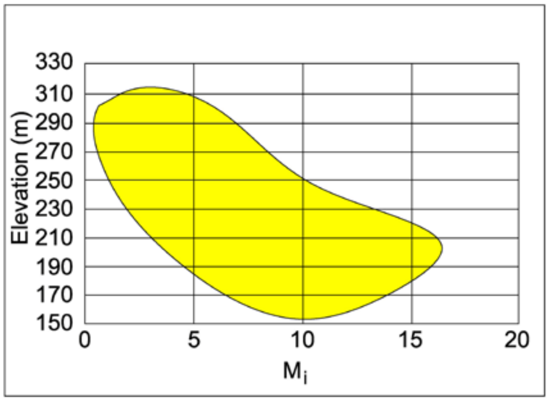

Figure 12. Typical range of M_i vs Elevation.

It has been shown that at pressures lower than σ'_p, the laboratory tests exhibit higher compressibility than what is experienced in the field. Therefore, the field M_i may be slightly higher than the laboratory M_i.

5.6 Post-consolidation Constrained Modulus

Post-consolidation Constrained Modulus (M_P) ranged from 0.9 MPa to 16.4 MPa with an average of 4.0 MPa for 65 tests. The correlation between M_P and e_0 was slightly better than the correlation between M_P and other index properties such as w_n and ɣ. Figure 13 presents the range of $M_P/(1+e_0)$ versus $1+e_0$ for all the tests and the best fit correlation as follows:

$$M_P/(1+e_0) = 31.433\,(1+e_0)^{-3.773} \qquad [4]$$

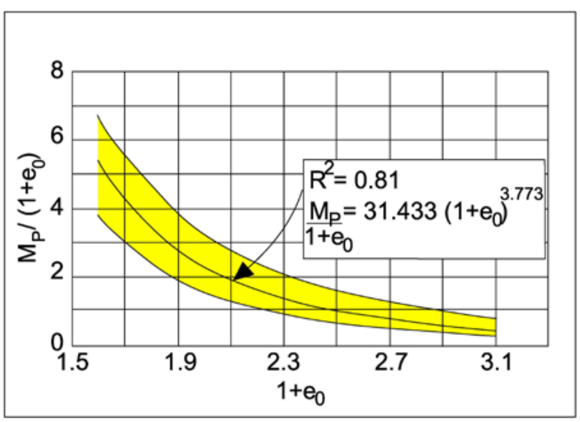

Figure 13. $M_p/(1+e_0)$ vs $1+e_0$ (all tests).

As noted before, the correlation between M_P and w_n or M_P and ɣ was relatively less reliable than Equation 4. For reference, Figure 14 presents the range of M_P versus w_n with regression factor (R^2) of 0.68 which is lower than the R^2 for Equation 4. The discrepancy may be due to the variation of in situ saturation of the clays. It should be noted that this correlation is generally equivalent to Equation 4.

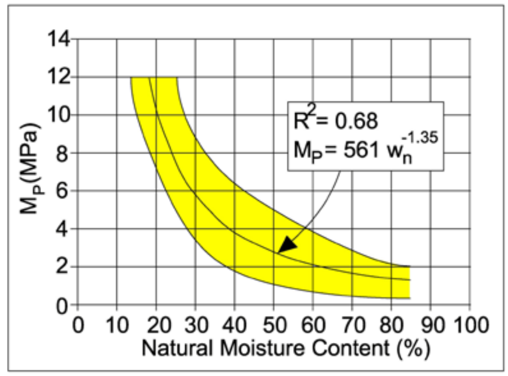

Figure 14. M_P vs w_n.

Atterberg Limits determination results were available for 52 of the consolidation tests. Correlations with w_L were poor with R^2 of 0.26.

It has been reported that for pressures higher than σ'_p, the settlement measured in the field is higher than the settlement predicted based on laboratory test results, hence, exhibiting lower M_P for the clay in comparison to the M_P obtained from laboratory testing. Therefore, in order to better evaluate the settlement of Barlow-Ojibway clay, the time dependent compressibility must also be considered.

5.7 Correlation of C_C and M_P

Figure 16 presents a plot of C_c vs M_P for all the tests. Regression analysis indicates a R^2 of 0.76 for the following correlation.

$$M_P = 1.98\,C_c^{-0.73} \qquad [5]$$

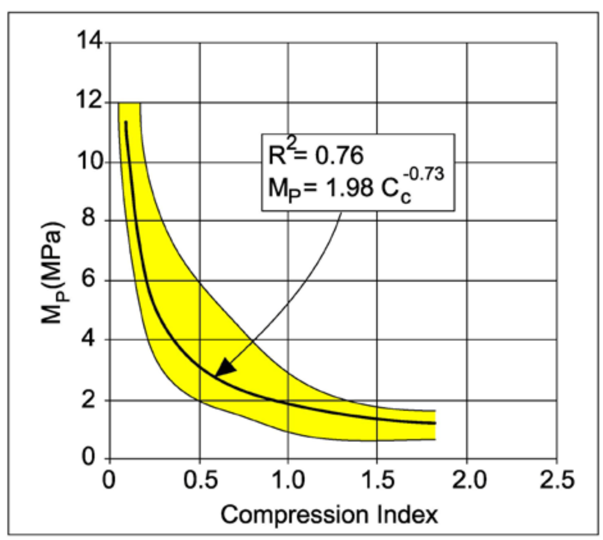

Figure 15. M_P vs C_c.

5.8 Comparison with Commonly Used Correlation of Clays

Figure 16 presents the typical range of C_c with e_0 for the Barlow-Ojibway clays (extracted from Figure 10) and sensitive Leda clays (Drevininkas et al 2014). The figure also presents a comparison with four well known published correlations between these two parameters.

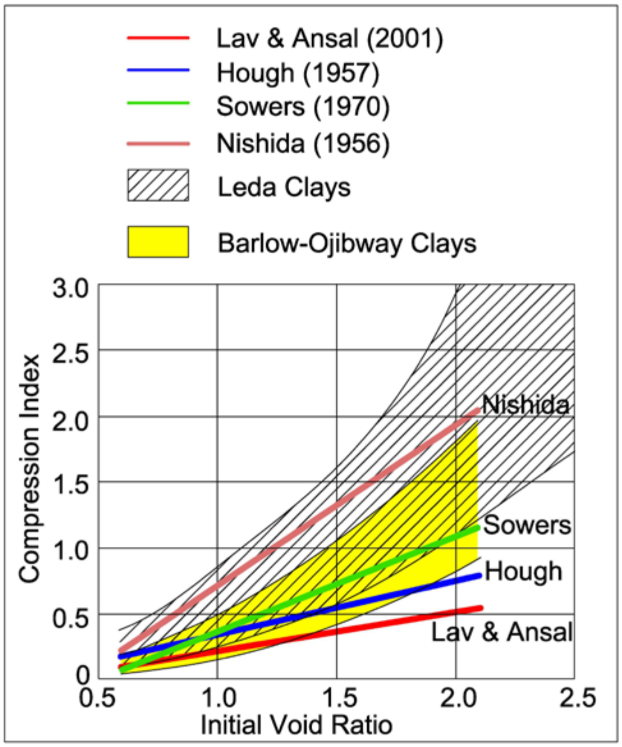

Figure 16. C_c vs e_0 correlation comparison for Barlow-Ojibway clays, Leda clays and published correlations.

As illustrated in the figure, the well known correlations by Hough (1957) and Lav & Ansal (2001) are not suitable for Barlow-Ojibway clays and Leda clays. Sowers (1970) correlation is not clearly suitable for Leda Clay, same as Nishida (1956) correlation for Barlow-Ojibway clays. Sowers (1970) correlation lies within the typical range for the Barlow-Ojibway clays; however, the regression factor of this correlation for the typical range of Barlow-Ojibway clays would be much less than 0.81. Therefore, the Sowers (1970) correlation is less reliable than Equation 3 presented in this paper for Barlow-Ojibway clays. Similarly, Nishida (1956) correlation lies within the typical range for the Leda clays; however, the correlation is much less reliable than the correlation studied for Leda Clay (Drevininkas et al 2014). This emphasizes the need for establishing specific correlations for geological deposits as opposed to global correlations for clays of different deposition, mineralogy and aging.

6 CONCLUSIONS

An analysis of the 67 high quality oedometer tests carried out in the Barlow-Ojibway clays in northern Ontario, below the clay “crust”, reveal good correlations with some index soil laboratory test results, as summarized below.

- The range of measured soil properties compared with geodetic elevation and depth, where a general trend is observed, have been presented.
- Poor correlation was found between C_r and index soil properties.
- Good correlations were found between C_c and e_0, with less reliable correlations with w_n and poor correlation with w_L.
- No reliable correlation was found for M_i with index soil properties.
- Good correlations were found between M_P and e_0, with less reliable correlations with w_n and poor correlation with w_L.
- An excellent correlation between C_c and M_P was found. This can assist geotechnical designers to allow for equivalent parameters to be used in different settlement analysis methods.
- Based on our assessment of the data, the lake was deposited at different elevations, with the higher ground surface elevations associated with the western portion of the deposit in the area of Longlac, with the lower ground surface elevations associated with New Liskeard in the eastern portion of the deposit. The lakebed was likely in the range of elevation 310 to 330m in the western portion of the study area and 190 to 230m in the eastern portion of the study area.
- Typical published empirical correlations (Hough 1957, Lav & Ansal 2001) are not suitable for Barlow-Ojibway clays or Leda clays. Other correlations (Sowers 1970, Nishida 1956) may lay within the typical range for Leda clays or Barlow-Ojibway clays; however, they are not very reliable. This emphasizes the need for geological deposition specific empirical correlations as opposed to global correlations for clays of different deposition, mineralogy and aging.

The correlations presented in this paper provide a basis for more cost effective preliminary settlement analysis and/or statistical analyses of the soil property at detail design stage for specific sites where there is limited number of tests for the project. Further interpretation using the field corrected C_c values could be carried out to review the effect on the above noted correlations.

Further analysis of the consolidation tests could be carried out to derive Janbu modulus numbers to provide an alternate settlement analysis method.

The M_P correlations could be further refined by analysing M_P for set ranges of stress levels. The M_P values and correlations presented could be used to calibrate CPTu interpretation in similar soils.

ACKNOWLEDGEMENTS

The writers would like to thank the Ministry of Transportation of Ontario for permission to present this paper. We would also like to thank Dr. Michael Nkemitag for translation of the abstract into the French language.

REFERENCES

Bjerrum, L. 1973. Problems of soil mechanics and construction on soft clays. *8th ICSMFE*, Moscow. Vol. 3, 111 - 159.

Casagrande, A. 1936, The determination of the pre-consolidation load and its practical significance. *Proceedings of the 1st International soil Mechanics and Foundation Engineering Conference*, Harvard University, Cambridge, Mass., Vol. 3: 60 - 64.

Drevininkas, A., Manzari, M., Sangiuliano, T. and Staseff, D. 2014. Geotechnical Characteristics of Leda Clay in the Ottawa Region. *Proceedings of 67th Canadian Geotechnical Conference,* Regina, Canada.

Eyles, N. 2002. *Ontario Rocks – Three Billion Years of Environmental Change*, Fitzhenry & Whiteside.

Hough, B.K. 1957. Basic Soils Engineering. The Ronald Press Company, New York, pp. 114-115.

Lav, M.A. and Ansal, A.M. 2001. Regression Analysis of Soil Compressibility. *Turkish Journal of Engineering and Environmental Science*, 25, pp. 101-109.

Lunne, T., Beere, T., Andersen, K.H., Strandvik, S. and Sjursen, M. 2006. Effects of sample disturbance and consolidation procedures on measured shear strength of soft marine Norwegian clays, *Canadian Geotechnical Journal*, 43(43): 726 - 750.

Morin, P., Leroueil, S., and Samson, L. 1983. Preconsolidation pressure of Champlain clays. Part 1. In-situ determination. *Canadian Geotechnical Journal*, 20:782-802.

Nishida, Y. 1956. A Brief Note on Compression Index of Soils, *Journal of Soil Mechanics and Foundations Division*, ASCE, 82, SM3, pp. 1027-1 to 1027-14.

Quigley, R. M. 1980. Geology, mineralogy, and geochemistry of Canadian soft soils: a geotechnical perspective, *Canadian Geotechnical Journal*, Volume 17 (1980), pp. 261-285.

Roy, M., Dell'Oste, F., Veillette, J. J., de Vernal, A., Hélie, J.-F., Parent, M. 2011. Insights on the events surrounding the final drainage of Lake Ojibway based on James Bay stratigraphic sequences, *Quaternary Science Reviews*, Volume 30 (2011), pp. 682-692.

Schmertmann, J.H. 1955. The undisturbed consolidation behavior of clay, *Trans. Am. Soc. Civ. Eng.,* 120: 1201 - 1227.

Sowers, G.B. 1970. Introductory Soil Mechanics and Foundations, The Macmillan Company, Collier-Macmillan Limited, London, 3rd Edition.