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Data collection and information management across Champlain Sea Clay deposits of Eastern Canada

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ABSTRACT
Several investigations have been undertaken during the past five decades to understand and interpret the glaciomarine clay deposits of eastern Canada. The focus of these investigations was mainly directed to study the behavior of Champlain Sea Clay, which is widely deposited in eastern Ontario and Western Quebec. Various properties of Champlain Sea Clay required for geotechnical investigations are typically derived from laboratory tests and in-situ field tests. Performing such tests routinely for the design of conventional projects such as the municipal or residential structures, is cost-prohibitive. There is a vast amount of data on these clay deposits in the literature; which include, Atterberg limits, particle size analysis, natural water contents, and unconfined compression tests. In addition, there is data available for interpreting the hydro-mechanical behavior, which include hydraulic conductivity, consolidation tests, and the shear strength properties. A wealth of data is compiled and synthesized into a searchable database such that it can be easily accessed. This article provides a summary of the methodology of how the Champlain Sea Clay soil properties information is compiled into an accessible database using Microsoft Access Relational Database. It also provides information on how the user can extract the required soil properties information of a specific location, from queries. The summarized information can also be useful for proposing empirical relationships that can be used in geotechnical engineering applications. The key objective of this paper is to alleviate or reduce soil testing and investigation costs for Champlain Sea Clay deposits, in conventional geotechnical engineering practice.

RÉSUMÉ
Plusieurs recherches ont été entreprises au cours des cinq dernières décennies pour comprendre et interpréter les dépôts d'argile glaciomarine de l'est du Canada. L'objectif de ces recherches était principalement d'étudier le comportement de l'argile de mer de Champlain, qui est largement déposée dans l'est de l'Ontario et l'ouest du Québec. Les diverses propriétés de l'argile de mer de Champlain requises pour les études géotechniques sont généralement dérivées d'essais en laboratoire et d'essais in situ sur le terrain. La réalisation régulière de tels tests pour la conception de projets conventionnels tels que les structures municipales ou résidentielles, est d'un coût prohibitif. Il existe une grande quantité de données sur ces gisements d'argile dans la littérature; qui comprennent les limites d'Atterberg, l'analyse de la taille des particules, la teneur en eau naturelle et les tests de compression non confinés. De plus, des données sont disponibles pour interpréter le comportement hydromécanique, notamment la conductivité hydraulique, les essais de consolidation et les propriétés de résistance au cisaillement. Une mine de données est compilée et synthétisée dans une base de données consultable de sorte qu'elle soit facilement accessible. Cet article fournit un résumé de la méthodologie de compilation des informations sur les propriétés du sol de l'argile de mer de Champlain dans une base de données accessible à l'aide de la base de données relationnelle Microsoft Access. Il fournit également des informations sur la façon dont l'utilisateur peut extraire les propriétés de sol requises d'un emplacement spécifique, à partir de requêtes. Les informations résumées peuvent également être utiles pour proposer des retations empiriques pouvant être utilisées dans des applications de génie géotechnique. L'objectif principal de cet article est d'alléger ou de réduire les coûts d'analyse et d'étude du sol pour les gisements d'argile de mer de Champlain, dans la pratique conventionnelle du génie géotechnique.

1 INTRODUCTION

Geotechnical engineering services are often expensive in comparison to other discipline services required for a civil engineering project. Due to this reason, more budget is typically allocated for procuring geotechnical services. However, in many scenarios, the allocated budget with in a project for engineering work such as analysis, design and technical reporting is rather limited. A large portion of the budget is consumed for tracing underground utilities, drilling operations, in-situ testing, safety precautions of the fieldwork such as traffic control, or assigning budget for the work of non-engineering staff for supervision of field investigations. In addition, a significant portion of the budget is spent on performing conventional laboratory tests that are required for the project. An overview of the project cost analysis undertaken by the first author during the past five years is shown in Figure 1. These results suggest that 59% of the budget is spent for field operation costs and 9% on laboratory testing. The remainder of 32% of the costs are spent on administration, engineering, analysis and technical reporting services. Also, in this cost analysis, based on the available financial records, no distinction could be made on the percentage of time and budget spent on administrative work versus technical work. The study suggests that the actual budget spent for engineering work is less than 30%. About 70% of the costs are related to the field and laboratory costs, in a typical project budget. Therefore, more financial resources can be allocated towards engineering analysis and design, if cost savings are achieved.

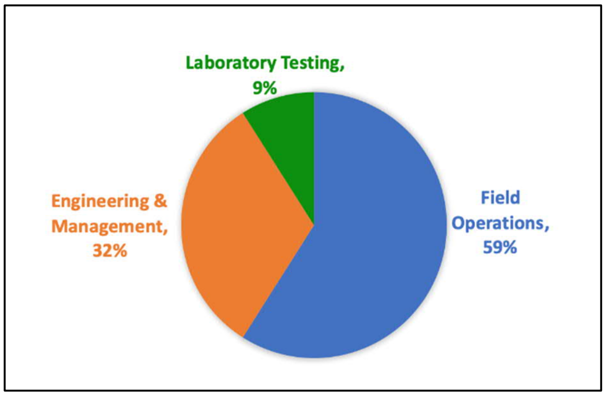

Figure 1. Average distribution of geotechnical project budget from 2015 to 2020

However, a delicate balance has to be maintained between adequacy of the amount of data that has to be collected and the engineering services that are required for a project. As a regulatory guideline, Professional Engineers Ontario states, “Practitioners should be sure to obtain equipment nameplate data; dimensions; detailed views of parts of the site, structures and or equipment; and samples, where appropriate” (PEO 2017). This statement suggests that the responsibility lies upon the engineer who seals the geotechnical report to ensure the site is properly tested, and the geotechnical properties of the project field are adequately represented. The PEO practice guideline also states, “Often, an engineer or client will arrange for test of … site material, such as soil or water, to be carried out by an independent testing or by a qualified tradesperson. Whenever possible, engineers should witness these tests to ensure they are preformed according to their detailed instructions, particularly when reliance must be placed on a relatively small number of tests” (PEO 2017). The main objectives of the regulation for accuracy of site characterization can be summarized in the following two essential mandates:

- Geotechnical engineer needs to ensure an adequate amount of data is gathered for site characterization
- In addition, engineer shall exercise due diligence to confirm the accuracy of the tests

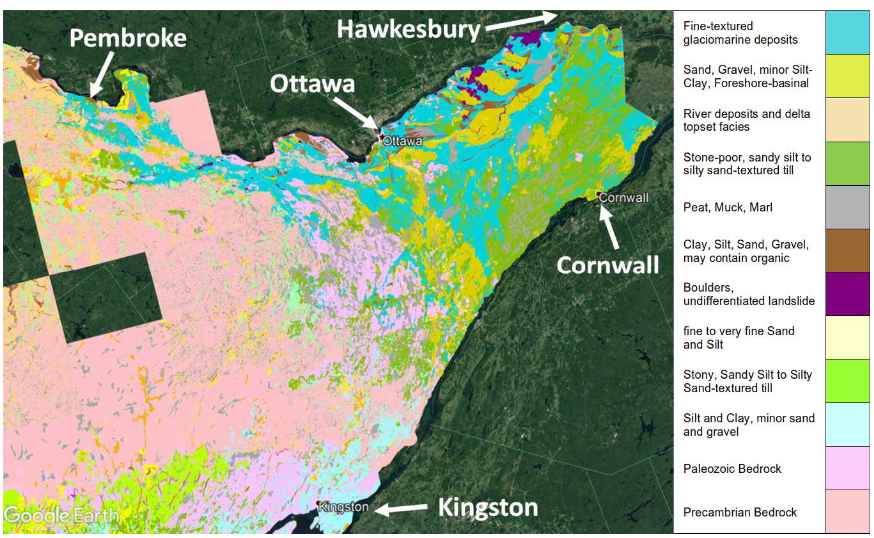

Figure 2. Distribution of Champlain Sea Clay in Eastern Ontario.

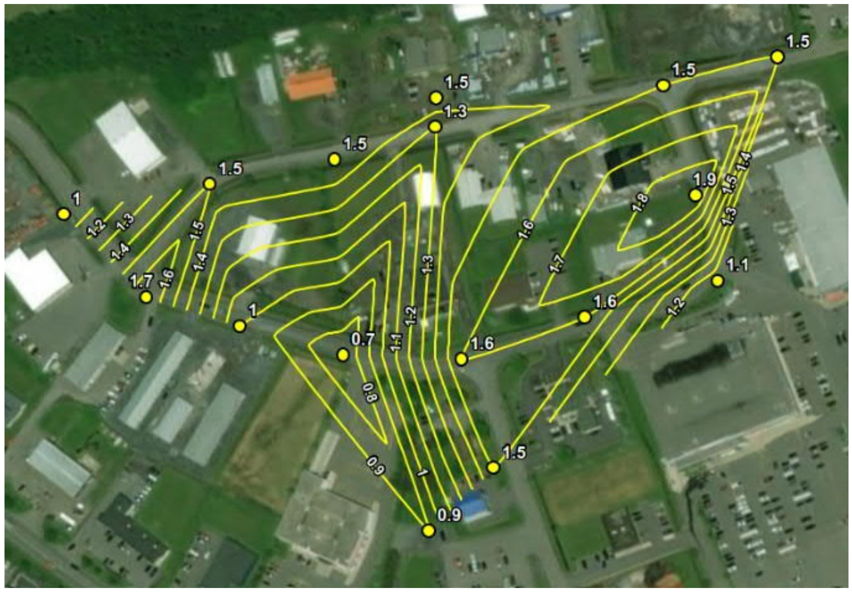

Figure 3. Interpreted desiccated clay layer thickness for shallow foundation design (from *Project specific contours, Russell, Ontario*)

Both “adequacy” and “accuracy” can be improved in a project by increasing the number of tests. In other words, the project site assessment will be more reliable, if it is based on more test results which include in-situ or laboratory tests or both. Standard error reduces inversely and proportionally due to an increase in the sample size. However, this is not possible in many scenarios of conventional geotechnical practice due to prohibitive costs associated with soil testing procedures. For this reason, the focus of the present research is directed towards gathering the existing geotechnical data collected from laboratory and field tests from investigations on Champlain Sea Clay, for the past 50 years from various sources. The key objective of the study is to help the practicing engineers, contractors and the researchers to mine the geotechnical data for a defined geographical limit, through the spatial distribution of the data. Such a mining technique for gathering the required information that is already available from earlier studies that is summarized in the literature is not only economical for use but also provides confidence for interpretation of limited case-specific project data obtained within a defined geographical zone.

The contents summarized in this paper is an ongoing research study. The project is at its early stages of development with respect to collection of the data. The data collection methods that are used to-date, are succinctly summarized. The main objectives of this study are;

- to provide an easily searchable database for a limited geographical region, predominantly covered by Champlain Sea Clay
- to synthesize the spatially distributed data of various Champlain Sea Clay properties.

As a first step, it was decided to gather the available data on the Champlain Sea Clay soil (this is also referred to as the Leda Clay) from the public access reports and the published literature. The area of data collection has been limited to Eastern Ontario; focusing mainly on the Ottawa region. The approximate area that covers this region is shown in Figure *2*. Leda Clay is widely distributed within the dark blue region and it is identified as “fine-textured glaciomarine deposits”. This figure is created by using surficial geology polygons provided by the Ontario Ministry of Energy, Northern Development, and Mines. Polygons are superimposed on the Google Earth platform for interactive viewing. The extent of Leda Clay as shown in Figure 2 is estimated approximately 7,000 km^2.

2 DATA COLLECTION AND SYNTHESIS.

This section provides details of a few examples of data mining. Data extraction can be merely statistical, such as demonstrating a given parameter for a limited geographical area, or it can be a combination of statistical interpolation and analytical calculations. Extracted data can be synthesized and can be used in routine geotechnical engineering practice or can be used to examine the validity of an existing correlation from the literature. The capability of handpicking data quickly with a certain degree of confidence one of the main advantages of this method.

2.1 Spatial distribution of the raw data

The relational database has three main tables connected in a hierarchy through primary keys. Data from various sources is systematically collected following consistent protocols. The data is easily accessible through three levels; site, probe location, and sample levels.

The data can be synthesized and stored virtually, which can be retrieved in the form of tables or can be simply retrieved as raw data. The database mainly facilitates in collecting raw data from boreholes based on the geographical coordinates using spatial distribution information. The database structure is schematically shown in Figure 4.

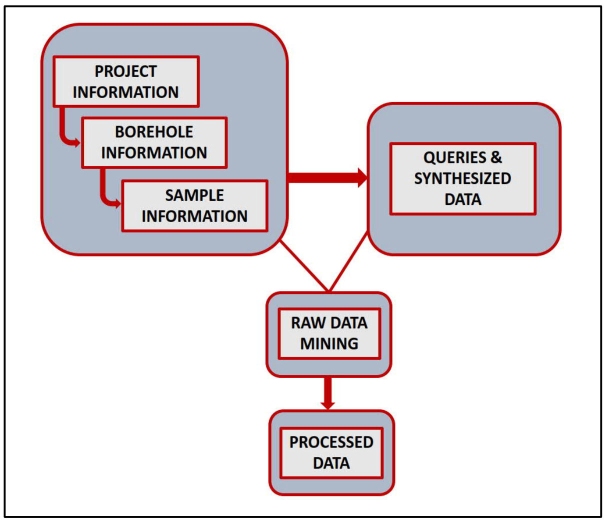

Figure 4: Schematic structure of data storage and extraction

An example is summarized below to demonstrate how spatial distribution of raw data is managed. Some geotechnical engineering projects require information about the thickness of the desiccated clay crust. Champlain Sea Clay layer is stiff and over-consolidated due to influence of weathering cycles such as desiccation or frost action. The weathering action can contribute to a reduction in the sensitivity of the clay (Barker et al. 2015). The authors, from their experience of investigating Champlain Sea Clay, have observed significant differences between the behavior of the desiccated clay layer and the softer underlying clay, from in-situ tests such as the standard penetration tests (SPT) and the vane shear tests (VST), from the measurements of undrained shear strength. In many scenarios, engineering judgement has to be used in the design or selection of construction methods taking account of the differences in the mechanical properties. Low-rise light-frame residential subdivisions or pavement projects are examples of projects that are affected by the thickness of the clay crust.

Figure *3* shows a thickness contour of the clay crust based on borehole data across a relatively extensive area. The presented data was extracted from the database and directly imported into ArcGIS software to create the image. The project showcased in Figure 3 is a publicly funded project for the Russell Township and information is available to the public. The project scope was specific and was directed towards design of a municipal infrastructure. The generated contours were used as a tool to demonstrate the need for excavation protection at various segments of the municipal roads. However, those contours can be also used for foundation design of infill development within that industrial park.

Information about the thickness of the desiccated clay crust is vital for several infrastructure projects. The Leda Clay that is not subjected to weathering action typically has a high water content; due to this reason, it is also highly sensitive. In many scenarios, as observed from site investigation results, the in-situ moisture content of the Leda Clay is higher than its liquid limit. High sensitivity and excessive moisture are an impediment for the use of the excavated clay as engineered fill or as imported material for construction of compacted clay liners. It is noteworthy that the liquid limit of Leda Clay is usually higher than the upper limit recommended for the design of clay liners. For this reason, this type of clay often needs to be mixed with other soils to meet the desired construction and design requirements such as the soil gradation or plasticity. If this is not achieved, and if the sensitivity of clay is excessively disturbed, transportation and mixing operations will be difficult or impossible. For example, a case study for Nouvelle Autoroute 30 in Quebec that has been documented, suggest that desiccation and weathering reduce the moisture content and sensitivity. This case study suggests desiccated Champlain clay could be compacted and used as earthwork material (Barker et al. 2015). If data for the desiccated crust thickness over a given area is available, the material volume that is required for a given project, can be easily calculated by GIS modeling.

2.2 Correlation between various tests

Field investigation studies (ASTM D1587 2015) require collecting in-situ soil samples that have to be tested in a laboratory (ASTM D2435 2011) using oedometers for the determination of consolidation parameters of cohesive soils, which may include preconsolidation pressure, compression and swelling indices and coefficient of consolidation. Such tests require services of trained technical personnel and extensive equipment for gathering information from in-situ and laboratory tests. These are also time consuming tests and expensive. To alleviate the costs, several studies have been undertaken on cohesive soils including Leda Clay (Trak et al. 1980) to correlate the pre-consolidation pressure of the in-situ clay to other soil properties that can be determined from simple tests. For example, it is widely accepted to estimate the pre-consolidation pressure to the in-situ undrained shear strength of the clay.

Bjerrum (1972) suggests a value of 0.22 for C_u/P_c' for Leda Clay. However, Tavenas et al. 1978 study suggests the ratio of C_u/P_c' varies between 0.21 and 0.26 with an average of 0.24. Other researchers suggest including a correction factor based on soil properties such as plasticity index to adjust the ratio of undrained shear strength to the pre-consolidation pressure such that $C_u/P_c' = f(I_p) = \mu$ (Mesri 1975). Leroueil et al. (1983) have provided C_u/P_c' relationship taking account the plasticity index of the soil as below:

[1] $C_u/P_c' = 0.2 + 0.0024I_p$.

Once adequate data is collected and summarized in to the database, it can be a valuable tool and facilitate the geotechnical engineer in the estimation of stress history of the area of interest. It is likely the samples data may be scattered both with respect to a given area and as well as depth. However, if more sample data is gathered, it can increase the accuracy of the estimation. Typically, detailed geotechnical investigations are undertaken only after decisions are made on the conceptual design. Therefore, estimating the stress history of Champlain Sea Clay at the conceptual stage of the design can be of great assistance in making decisions and planning of the project.

2.3 Shear Strength Prediction for Unsaturated Soils

Shear strength of the soil is one of the key properties required in the design of several geotechnical infrastructure that include shallow and deep foundations, retaining walls, slopes and embankments. Conventional soil mechanics principles are widely used in the design of geotechnical infrastructure assuming saturated soil conditions. However, the natural ground water table is typically at a greater depth in many regions of the world (i.e., semi-arid and arid regions). The natural soil above the groundwater table is typically in a state of unsaturated condition. The apparent cohesion within the unsaturated zone is significantly influenced due to environmental factors, which contributes to moisture content changes, and influences the matric suction. Matric suction is a key stress state variable that influences the soil behavior in the unsaturated zone. The top layer of Leda Clay deposits are typically desiccated in the Ottawa region and hence are in a state of unsaturated condition. This desiccation may be attributed to permanent dewatering, wetting and drying, or freeze-thaw cycles. The shear strength behaviour of desiccated clay and the saturated clay below groundwater are significantly different. For this reason rational design of geotechnical infrastructure should be based on taking account of the influence of both saturated and unsaturated soil conditions.

Experimental determination of the shear strength behavior of unsaturated soils is time consuming and expensive. For this reason, empirical procedures are proposed for the prediction of shear strength of unsaturated soils (Garven and Vanapalli 2006). The shear strength of unsaturated soils is predicted using the soil-water characteristic curve (SWCC), which is defined as a relationship between the water content (volumetric or gravimetric) and the saturated shear strength parameters (Vanapalli et al. 1996). A succinct background on the shear strength of unsaturated soils and how it can be predicted is summarized below.

Fredlund et al. 1978 extended Mohr-Coulomb theory for interpreting the shear strength of unsaturated soils using the equation below.

[2] $\tau_f = c' + (\sigma_n - u_a)tan\phi' + (u_a - u_w)tan\phi^b$

τ_f : shear strength of unsaturated soil
c' : soil cohesion (effective)
$(\sigma_n - u_a)$: net normal stress (normal to the failure plane)
ϕ' : angle of internal friction (for saturated soil)
$(u_a - u_w)$: matric suction
ϕ^b : angle of shearing resistance contribution from matric suction

The angle of shearing resistance with respect to matric suction is non-linear and can be expressed using the below relationship.

[3] $tan\phi^b = \partial\tau/\partial(u_a - u_w)$

Vanapalli et al. 1996 proposed a simple procedure for predicting the shear strength using Eq. [4]. The shear strength contribution due to matric suction can be expressed as functional relationship using the SWCC. Therefore, the shear strength equation can be expressed in terms of normalized water content.

[4] $\tau = [c' + (u_a - u_w)\tan\phi'] + (u_a - u_w)[(\Theta^{\kappa})\tan\phi']$

Θ is the normalized volumetric water content, and κ is the fitting parameter.

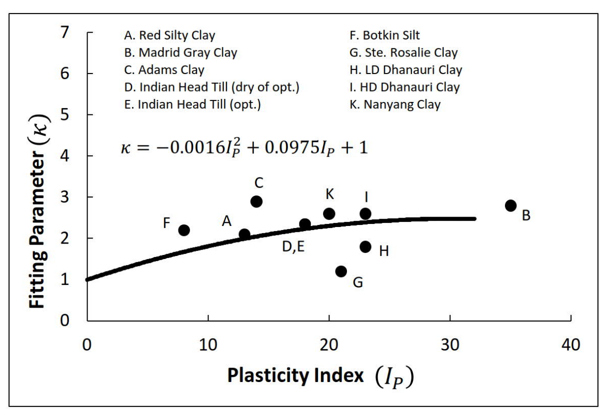

Figure 5. Relationship between κ and I_p for natural, statically compacted soils (Garven and Vanapalli 2006)

Vanapalli and Fredlund (2000) provided an empirical relationship for the prediction of the fitting parameter from plasticity information as given below.

[5] $\kappa = -0.008 I_p^2 + 0.0975 I_p + 1$

Using the published data from the literature, Garven and Vanapalli (2006) have modified Eqn, [5] as given below:

[6] $\kappa = -0.0016 I_p^2 + 0.0975 I_p + 1$

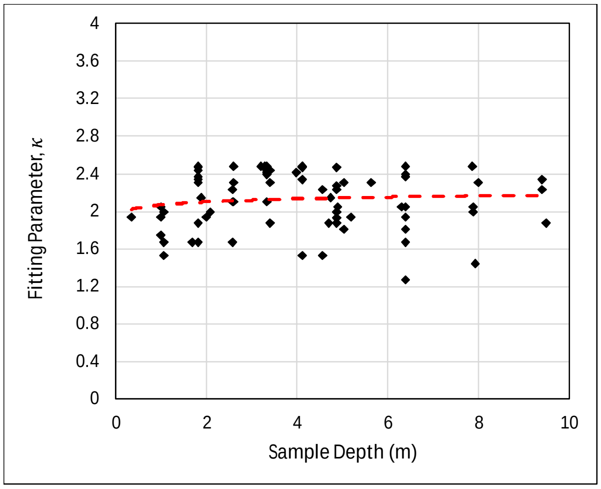

Figure 6. Distribution of fitting parameter κ vs. depth based on soil plasticity index

The fitting parameter, κ required for predicting the shear strength equation was calculated using Eq. [6] for Champlain Sea Clay from plasticity index information gathered at different depths (Figure 6). The data of estimated fitting parameter, κ values versus the sampling depth have a standard deviation of σ = 0.31. The mean value for the fitting parameters estimated for the Ottawa Champlain Sea Clay is 2.12, which is close to the value suggested by Vanapalli et al. (1996) for a compacted soil, with approximately similar properties as Leda Clay.

Research studies from back calculations for determining fitting parameter, κ from experimental studies on Champlain Sea Clay are in progress. A simple technique will be proposed for determining fitting parameter, κ from unconfined compression test results. Also, an experimental technique planning is in progress for determining the shear strength of unsaturated Champlain Sea Clay using conventional direct shear testing equipment. These experimental studies will provide more credence for suggesting a κ value for Champlain Sea Clay. More details and discussions are not included because it is beyond the scope of the present study of this paper

3 DATABASE STRUCTURE

This paper is a method statement for an ongoing research study. The research is still at the data collection stage and many different phases are in progress. The focus of the research is mainly directed towards gathering various soil properties data of Leda Clay of eastern Ontario that can be used in geotechnical practice. In this section main sources of data are identified and the database structure is explained.

3.1 Data Resources

Most of the reports submitted to the public sector as part of the publicly funded projects are available to the public. The reports completed by the industry for the City of Ottawa are rich sources of information. The authors did not have access to the database from City of Ottawa geotechnical reports. However, a substantial number of other reports were obtained through the Development Application Search capability of the City of Ottawa website (City of Ottawa 2020). A few of those reports were found by a targeted search of specific projects tender packages. The foundation engineering reports which have been submitted to the Ministry of Transportation Ontario (MTO) that are available through the Ministry's Foundation Library (MTO 2018) were also used in this study. This library offers an interactive map of all locations with available data. By superimposition of this interactive map on the surficial geology maps of Ontario, the reports pertinent to Leda Clay were handpicked. Surficial geology maps used for this research were those published by the Government of Ontario (OGSEarth 2019). In addition, reports that have been completed by the senior author on the Ottawa area projects for the past several years, were used for this research.

3.2 Database Structure

The database is tailored to capture specifics of Leda Clay as well as some generic project information. The data is compiled through a three-tier relational database. The first level includes all general information and project references to identify the project, such as name, address, reporting date, and the author or the publisher. The second level narrows down to each probe and includes information such as geographical coordinates, investigation method, and investigation date of each borehole, ground surface elevation, groundwater depth, and depth of investigation. Also, when information is available, the thickness of the desiccated clay crust and the total thickness of the clay are recorded. The third tier of information provides information at the sample level. All samples and in-situ tests of each borehole are recorded. Information at this level includes sample identification, depth, and values of in-situ tests, natural water content, plasticity parameters, gradation, consolidation parameters, and other laboratory tests when noted in the geotechnical report. Through the relational structure of the database, each individual sample can be traced back to the respective borehole and ultimately to the project for identification.

4 QUERIES AND REPORTING

The database is established in Microsoft Access, which is flexible and a powerful tool for making queries and preparing reports from it. The reports can be generated in the form of virtual tables that can be customized based on the users' needs. Calculations can be performed directly based on queries or on the data exported to other software. The relationship becomes more useful during the analysis period as the user can easily compare data from all three main tables together. The query forms allows the user to select any field from various tables across the whole database and retrieve data as needed for academic research or for geotechnical engineering practice applications. The data from queries can also be exported to other software such as MS Excel or Matlab to perform further analysis, as required for research purposes or for use in conventional industry geotechnical reports.

5 CONCLUSION

This paper summarizes details of data collection methodology for gathering various soil properties information of Champlain Sea Clay, which is widely distributed in eastern Canada. In addition, information of how the database can be used for some conventional geotechnical engineering practice applications is provided, with examples. This is an ongoing study; however, to date, a large amount of data has been gathered from the publicly accessed geotechnical reports and the published literature on the Champlain Sea Clay of eastern Canada. The summarized research in this paper, is still in its preliminary stage. As more data is collected in the database, the gathered information can be useful for developing empirical relationships that can be used in engineering practice applications. Most importantly, the developed data mining tool can alleviate or significantly reduce conventional laboratory tests on Champlain Sea Clay. In other words, this database can contribute in savings both with respect to time and finances to the users.

REFERENCES

ASTM D1587. 2015. ASTM D1587 / D1587M - 15 Standard Practice for Thin-Walled Tube Sampling of Fine-Grained Soils for Geotechnical Purposes.

ASTM D2435. 2011. ASTM D2435/D2435M-11 Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading.

Barker, C., Phear, A., Côté, F., and Cueto, D.G. 2015. Nouvelle Autoroute 30: A Champlain clay crust earthworks case study. Canadian Geotechnical Journal, **52**(3): 295–304. doi:10.1139/cgj-2013-0388.

Bjerrum, L. 1972. Embankments on soft ground. *In* ASCE Specialty Conference on Performance of Earth and Earth Supported Structures. p. Vol.2, pp.1–54.

City of Ottawa. 2020. Service Ottawa Development Application Search. Available from https://app01.ottawa.ca/postingplans/home.jsf?lang=en.

Fredlund, D.G., Morgenstern, N.R., and Widger, R.A. 1978. The shear strength of unsaturated soils. Canadian Geotechnical Journal, **15**: 313–321.

Garven, E.A., and Vanapalli, S.K. 2006. Evaluation of empirical procedures for predicting the shear strength of unsaturated soils. *In* 4th International Conference on Unstaturated Soils.

Leroueil, S., Tavenas, F., and Le Bihan, J. 1983. Proprietes caracteristiques des argiles de l'est du Canada. Canadian Geotechnical Journal, **20**: 681–705.

Mesri, G. 1975. Discussion on new design procedure for stability of soft clays. ASCE Journal of the Geotechnical Engineering Division, (101): 409–412.

MTO, M. of T.O. 2018. Foundation Library. Available from http://www.mto.gov.on.ca/FoundationLibrary/index.shtml.

OGSEarth, M. of E.N.D. and M. 2019. OGSEarth. Available from https://www.mndm.gov.on.ca/en/mines-and-minerals/applications/ogsearth.

PEO, P.E.O. 2017. Professional Engineering Practice. *In* Safety and Reliability.

Tavenas, F., Blanchet, R., Garneau, R., and Leroueil, S. 1978. The stability of stage-constructed embankments on soft clays. Canadian Geotechnical Journal, **15**: 283–305.

Trak, B., Leroueil, S., and Roy, M. 1980. A new approach to the stability analysis of embankments on sensitive clays. Canadian Geotechnical Journal, **17**: 526–544.

Vanapalli, S.K., Pufahl, D.E., and Fredlund, D.G. 1999. Interpretation of the shear strength of unsaturated soils in undrained Loading conditions. 52nd Canadian Geotechnical Conference, Regina, Saskatchewan, (December): 643–650.

Vanapalli, S.K., Fredlund, D.G., Pufahl, D.E., and Clifton, A.W. 1996. Model for the prediction of shear strength with respect to soil suction. Canadian Geotechnical Journal, **33**: 379–392.