Hydraulic Properties of Glacial Deposits Based on Large Scale Site Investigation

Les propriétés hydrauliques des dépôts glaciaires basées sur une enquête de chantier à grande échelle

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ABSTRACT: Glacial deposits by nature comprise variable soil types in relatively short distances. Hydraulic conductivity (K) is the most important parameter in design of construction dewatering for underground structures. However, determination of proper design values for K is not an easy task. Due to the inherent variable nature of the glacial deposits, even conventional pumping tests may not provide reliable design parameter due to its smaller zone of influence compared to that of the actual dewatering for a structure. This paper describes the methodology created for establishing more representative design values for hydraulic conductivity of glacial deposits during a large scale subsurface investigation for planned tunnels. The subsurface investigation involved 400 boreholes, including 88 slug tests and 16 pumping tests. A relation was established between K obtained from the field tests (K_{field}) and K calculated by applying Kozeny-Carman formula (K_{KC}). Subsequently, the calibrated K-C formula was applied to 1,200 grain size analyses conducted on various soil types. The calculated and measured K were used to form statistical analysis of the parameter and provide more reliable design values for dewatering.

RÉSUMÉ : Les dépôts glaciaires comprennent des sols variables à travers des distances relativement courtes. La conductivité hydraulique (K) est le paramètre le plus important qui est nécessaire durant la construction des structures souterraines. Cependant, la détermination des valeurs de calcul appropriées pour K n'est pas une tâche facile. à cause de la nature variable des dépôts glaciaires, même les essais de pompage peut-être ne fourniront pas des résultats fiables pour une bonne conception pour une bonne conception parce que les structures déshydratés ont une plus grande zone d'influence. Ce document décrit la méthodologie créée pour établir les paramètres de conception plus représentatives au cours d'une enquête de chantier à grande échelle pour les tunnels de métro prévues. L'étude a porté sur 16 essais de pompage avec des puits d'observation associés, et 88 essais de conductivité hydraulique. Une relation a été établie entre K obtenue à partir des essais sur le terrain (K_{field}) et K calculé en appliquant la formule de Kozeny-Carman (K_{KC}). Par la suite, la formule de K-C calibrée a été appliquée à des analyses granulométriques effectuée 1200 échantillons. Les valeurs de K calculées et mesurées ont été utilisées pour former une analyse statistique, et pour fournir des valeurs plus fiable.

KEYWORDS: Kozeny-Carman formula, hydraulic conductivity, Glacial Tills, dewatering.

1 INTRODUCTION

The Greater Toronto and Hamilton Area (GTHA), located in southern Ontario, is Canada's largest and fastest growing urban region. The Government of Ontario Province through its transportation authority known as Metrolinx, has embarked in a massive transportation plan called "The Big Move", which is a 25-year, $50 billion plan that will transform regional transportation across the GTHA. The Eglinton Scarborough Crosstown (ESC) Light Rail Project is part of that Big Move program. The ESC is a 19-kilometre light rail transit line (LRT) that will run along Eglinton Avenue, connecting west to east of the city. Eleven kilometers of the alignment will be tunneled underground, crossing well established urban areas which are densely populated and congested. The tunnel construction is divided in two contract packages: West Twin Tunnels Construction and East Twin Tunnels Construction, with Yonge Street the dividing limit. Dewatering operations will be required for a total of twenty four structures along the tunnel alignment: sixteen cross passages, four launch and exit shafts, and six emergency exit buildings.

In order to meet a very tight schedule while properly managing subsurface risk and support the design of the tunnel, an aggressive multi-phase geotechnical investigation program was undertaken. The geotechnical investigation for the west and east tunnel contracts was conducted during a two-stage program between 2010 to mid-2012; which followed by a hydrogeological study for each section. In summary, about four hundred (400) shallow and deep sampled boreholes were advanced including three hundred (300) monitoring wells along the subject alignment to obtain information regarding the subsurface stratigraphy and groundwater conditions. Furthermore, eighty eight (88) slug tests and sixteen (16) pumping tests (150 mm O.D.) were completed as part of the site specific hydrogeological study. At the time of preparation of this paper, only the results of eight (8) pumping tests for the west tunnels are available and used in analyses.

Due to project's very tight schedule and ongoing progress of design, the proposed locations of some structures were revised after completion of the pumping tests. Furthermore, it was not practical to conduct the pumping tests for all of the structures. Innovative techniques were developed and used to establish more representative design value of hydraulic conductivity while not having pumping test at exact location of each structure and also consider the inherent variable nature of the glacial deposits. This paper describes the methodology developed and summarizes the range of hydraulic conductivity for various types of glacial deposits obtained from this large scale subsurface investigation which is generally more refined than older published range for the same deposits.

2 GEOLOGY SETTING

A detailed regional description of the Quaternary geology of the project area can be found in the Ontario Geological Survey Map (Sharpe, 1980). The soil deposits in the project area are result of glacial depositional systems that took place during various glacial periods. From the published geological data, the GTHA experienced three glacial and two interglacial periods. This

fluctuating glacial advance and retreat produced a complex distribution of over-consolidated glacial till layers, separated by interstadial and interglacial stratified deposits of glacio-lacustrine plastic silt/clays and non-plastic silt/sands.
The subsurface overburden encountered during the site investigation were initially classified into 17 different soil types (Types 1 through 17). The soil classification system followed the modified version of Unified Soil Classification System. Identification of soil origin as "till" was based on their heterogeneous structure, the relatively broad grain size distributions and the documented local geology. Many of the different soil types demonstrate relatively comparable engineering characteristics and may possibly have similar geological origin. Consequently, the various soil types were consolidated into six engineering classes (Classes A through F). The six soil classes are as follows:

- Class A: Fill and Topsoil
- Class B: Interstadial Sand to Gravel
- Class C: Interstadial Silt to Sand
- Class D : Non-Plastic Till
- Class E : Plastic Glacio-lacustrine
- Class F : Plastic Till

Class B was divided into two subclasses based on the percentage of silt and clay particles (<75 μm). Sandy soils with less than 20% silt and clay particles were grouped under Class B2,3,4 and the rest (> 20% silty and clay) under Class B5,6.

3 ESTABLISHING HYDRAULIC CONDUCTIVITY

Glacial deposits by nature comprise of variable soils types in relatively short distances. Due to the inherent variable nature of the glacial deposits at project area, conventional filed pumping tests may not provide fully reliable results for a proper dewatering calculation as the zone of influence of a pump test may only extend a few tens of meters. On the other hand, the actual dewatering volume of a structure is affected by the characteristics of surrounding soil within a few hundreds of meters. Furthermore, the pumping tests were not necessarily at the exact location of some structures.

It became necessary to complement the hydraulic conductivity values obtained through field testing in order to expand the test results to a larger domain or be able to focus on any specific area. It was decided to use the available semi-empirical methods/formulae in literature to complement hydraulic conductivity values obtained through filed testing with predicted values based on index properties such as grain size distributions, pore size distributions and/or specific surface. The following sections will outline the procedure followed to predict hydraulic conductivities and provide design parameters.

3.1 *Kozeny-Carman formula*

Since Kozeny (1927) introduced his theory for a series of capillary tubes and Carman (1938 and 1956) followed this work and provided formulations that takes into the account the tortuosity of the flow path of a fluid in a porous medium. The following formula presented by Carman was then referred to as the Kozeny-Carman (K-C) formula (Carrier, 2003).

Details of the formula can be found in the subject references. In summary, the hydraulic conductivity of the soil can be estimated as follows:

$$K = 1.99 \times 10^4 \left(100\% / \left[\Sigma\{f_i / (D_{li}^{0.5} \times D_{si}^{0.5})\}\right]\right)^2 (1/SF^2)[e^3/(1+e)] \quad (1)$$

Where, e is the void ratio; SF is a shape factor; f_i is the fraction of particles between two sieves (%), denoting the larger sieve with (l) and the smaller one as (s) in, and $D_{ave\text{-}i}$ = $(D_{li} \times D_{si})^{0.5}$ is the average particle size, in cm, between two sieve sizes.

The Kozeny-Carman formula takes into account specific surface area of full range of particle sizes and soil void ratio which leads to better accuracy than the famous Hazen formula (Lambe and Whitman 1969) in predicting the hydraulic conductivity for a wide range of soils. Notwithstanding the above, the application of K-C formula is constrained by almost the same limitations as Hazen (Carrier 2003). Such constrains, as discussed below, arise when dealing with soils at the extremes of any spectrum such as the grain size, particle size distribution, particle shape, and particles orientation (anisotropy).

The formula does not account for the electrochemical forces between particles and particles and water which disqualify the formula from being applied to clayey soils. In addition, the formula assumes laminar flow, which may not be satisfied in gravels and gravelly sands. The formula does not produce a close estimate to the specific surface area of particles with extreme shapes such as platy or flakey particles. Therefore, the K-C formula may not be applicable in these cases or can be applied after replacing the calculated specific surface area by the measured value. Also, K-C formula does not account for soil anisotropy which is more pronounced in natural deposits than for laboratory constructed samples.

Locat et al (1984) measured the specific surface area (S) for several clays and found that clays with low plasticity (8 < PI < 15) have S between 23 and 30 m^2/kg and is independent of the percentage of soil finer than 2 μm. Chapuis and Aubertin (2003) picked a constant number between 23 and 30 m^2/kg as an estimate for S of the soil fraction finer than 2 μm and calculated S for the fraction coarser than 2 μm as per original K-C formula. Consequently, the results of these hybrid methods in using K-C formula were in good agreement with measured hydraulic conductivities in laboratory for clayey soils with PI<15. In this study, the approach proposed by Chapuis and Aubertin (2003) was followed for plastic glacial tills with PI less than 15. However, the effect of weathering and factures in the upper portion of the clayey till deposits must be considered in any assessment (McKay, 1993; Hendry, 1982).

3.2 *Site specific correlation factor for K-C formula*

This section outlines the work completed in the field to obtain in-situ hydraulic conductive (K) for the different soil classes and explains the approach followed to establish site specific correlation factor for using K-C formula.

Hydraulic conductivities for each soil class were measured in the field by a combination of pumping tests and/or falling or rising head slug tests. The results of 8 pumping tests with associated observation wells and 88 slug tests conducted along the tunnel alignment, distributed among six soil classes are used in this study. The number of the field tests performed on the aquifers' materials was greater than those performed on the other soil types. However, a significant number of the tests were performed on both plastic and non-plastic tills.

One grain size distribution analysis was conducted, as minimum, on the soil samples recovered from within the screen interval of the 88 slug tests and pumping tests with associated observation wells. These grain size distributions were determined by undertaking sieve analysis, in accordance to ASTM C136-06, and the hydrometer test, in accordance to ASTM D422-63. These grain size distributions analyses were used to calculate K based on the K-C formula. After excluding the tests for samples with PI >15 and/or field test conducted in the clayey till deposits with obvious signs of weathering and fracture, K-C formula was applied to about 80 grain size analyses that were screened as suitable (not within the limitations of the formula) and correspond with K obtained from field tests. As a result, for every in-situ measured K in the field (K_{field}) there is a corresponding predicted K from applying KC formula to the grain size analysis associated with the screen interval (K_{KC}), as shown in Figure 1.

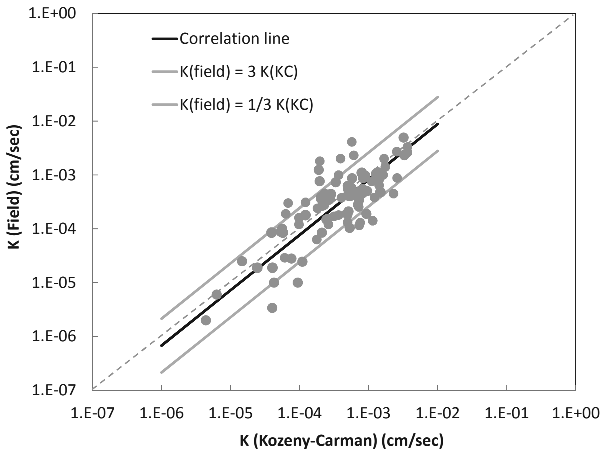

Figure 1 In-situ measured field hydraulic conductivity versus calculated by Kozeny-Carmen Formula (K_{KC} vs. K_{field})

The dashed line represents the equality line and the solid black line represents the site specific correlation line which has a slope shown in equation (2).

$$\log K_{field} = 1.03\times\log K_{KC} \qquad (2)$$

The grey lines in Figure 1 represent the boundaries that encompass 90% of the data points. These lines have the same slope as the correlation line with ±0.5 offset in the log-log scale. This indicates that Kozeny-Carmen formula with incorporation of the site specific correlation factor of 1.03 (equation (2)) predicts a K value ranging between 1/3 to 3 times the in-situ measured field hydraulic conductivity (K_{field}) for the glacial deposits in this specific site. These conclusions are comparable to the margin obtained from laboratory permeability test results shown by Chapuis (2002) and Chapuis and Aubertin (2003).

3.3 *Overall hydraulic conductivity for each soil class*

Hydraulic conductivity (K) values for each soil class of glacial deposits were calculated using the K-C formula as per method described in the previous sections for about 1,200 grain size analyses conducted on various soil types along the alignment. Equation (2) is then used to correct K_{KC} assuming that 90% of the predicted values fall between 1/3 to 3 times the actual K in the field. The statistical parameters were calculated for the corrected K_{KC} obtained for each soil class in conjunction with the K values directly obtained from field tests (slug and pumping tests). The statistical distribution of K for each soil class is plotted in histograms as shown in Figure 2a to 2e.

The K values obtained from the field tests conducted in the plastic till deposits (Class F) with obvious signs of weathering and fracture has also been added to the calculated K values and other field measurement results which all together included in the statistical distribution of K for Class F (Figure 2a). Generally, the higher end of the K distribution in Figure 2a is associated with the field measured hydraulic conductivity in the fractured plastic till. This is in conformance with the finding of other studies in similar soil condition (e.g., D'Astous 1989, Ruland 1991). Although, some of the slug tests conducted on this fractured zone were as low as the results typically associated with soil matrix values; which could by the results of the smeared zone tend to form around augered boreholes.

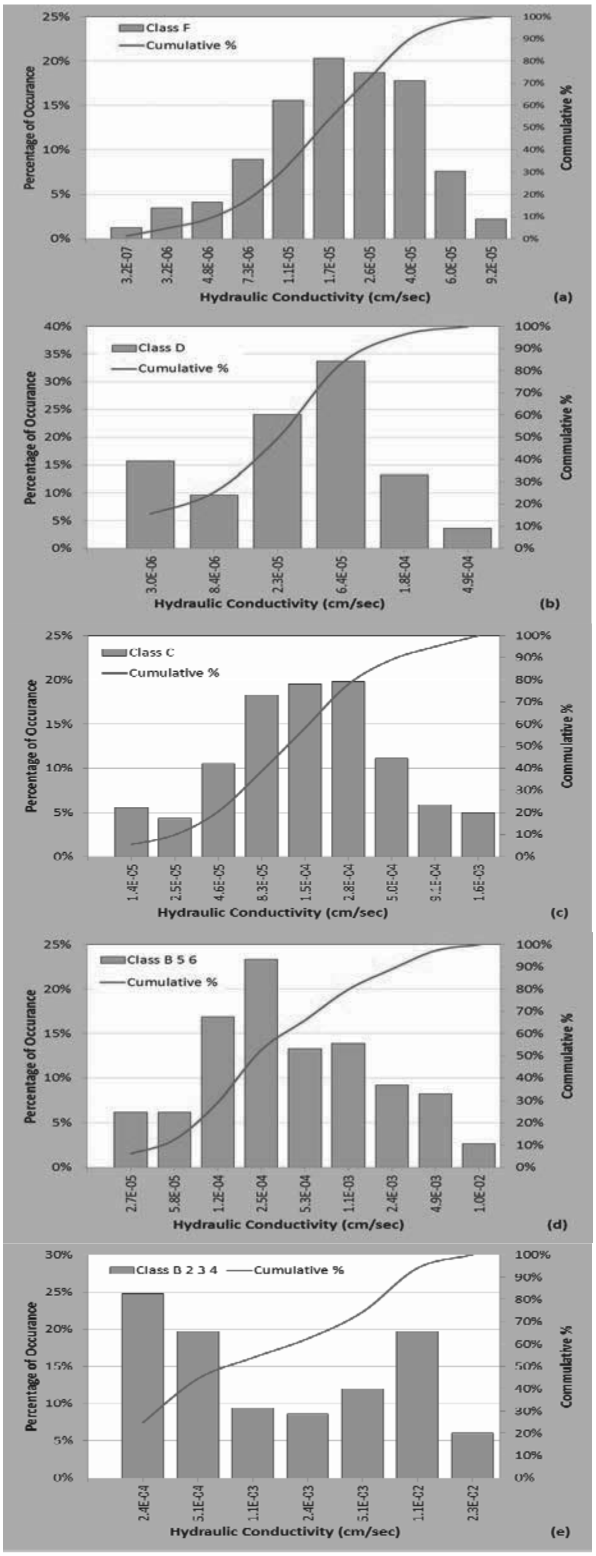

Figure 2a to 2e Statistical distribution of hydraulic conductivity for various soil classes of glacial deposits obtained from the investigation.

The K values for Class B2,3,4 (interstadial sand with less than 20% fines) fit a bimodal distribution (Figure 2e). Further review of the resutls indicated that the higher peak (10^{-2} cm/s) is associated to sand with leass than about 10% fine; while the rest of the class resutled to the lower peak.

3.4 *Design hydraulic conductivity for structures*

The zone of influence for 72 hours pumping tests ranged from 15 m to less than 100 m, depending on the location. On the other hand, the zone of influence for actual dewatering volume of the structures would be a few hundreds of meters and therefore, the dewatering volume would be affected by the characteristics of surrounding soil within this larger zone. In order to assess the reliability of the pumping test results for dewatering calculation, the uniformity of the soil within the dewatering zone was verified using the correlation described in the previous sections.

For each structure location, a zone of influence of 350 m radius is assumed. Corrected K_{KC} in conjunction with K values directly obtained from field tests (slug and pumping tests) within the assumed zones around each structure were pulled out of the overall data available. Subsequently, the statistical distributions of K-values for every soil class encountered within the dewatering zone were prepared for each structure. Examples of the cumulative distributions are shown in Figure 3a and 3b for Structure No.1 and No.2.

Based on the localized distribution of the K-values for each structure, the pumping tests results for some structures fall within 70 percentile or higher; on the other hand, the results for other structures could be as low as 20 to 50 percentile.

A detailed review of the results and interpretive subsurface profile showed that generally when the zone of the influence of the pumping tests was small, the K obtained from pumping test tends to be on the lower side of the cumulative distribution. This has also been augmented where random presence of pockets/seams of Class C soil within Class B deposits has dominant effect on pumping test results. The design K-value for dewatering calculation has been selected based on the result of the localized distribution of the K-values prepared for each structure. Two examples are shown in Figure 3.

4 CONCLUSION

Glacial deposits comprise of variable soil types in relatively short distances. Conventional pumping tests may not provide fully reliable results for a proper dewatering calculation as the zone of influence of a pump test may only extend tens of meters while the actual dewatering volume of a structure is affected by the characteristics of surrounding soil within hundreds of meters. Presence of pockets/seams with higher silt content within sandy deposits has dominant effect on pumping test results. Smaller the zone of influence of the pumping tests, K obtained from the test tends to be on the lower side of the cumulative distribution for the dewatering zone of influence. The pumping test results for some structures could be as low as 20 to 50 percentile of accumulative distribution. It is imperative to assess the reliability of the pumping test results for dewatering calculation in the variable glacial deposits; particularly when the zone of the influence of the pumping tests is relatively small.

The Kozeny-Carman formula takes into account specific surface area of full range of particle sizes and soil void ratio and proven to provide reliable predictions of K for wide range of soils. Based on the results of this large scale investigation, Kozeny-Carmen formula with incorporation of the site specific correlation factor, predicts K values ranging between 1/3 to 3 times the in-situ hydraulic conductivity (K_{field}) for the glacial deposits. This provides a powerful tool in verifying the reliability of pumping test results in glacial deposits. However, careful consideration must be given to proper interpretation of the field test results and applicability of the formula to site conditions.

It also should be noted that K of weathered zone of clayey deposits is controlled by flow through the fractures. The field K measured in this zone could be up to a few orders of magnitude greater than the clay matrix. Field measurements in this zone may also be sensitive to smearing during the installation of piezometers. Physical scale of field measurements may strongly influence the resulting hydraulic conductivity values.

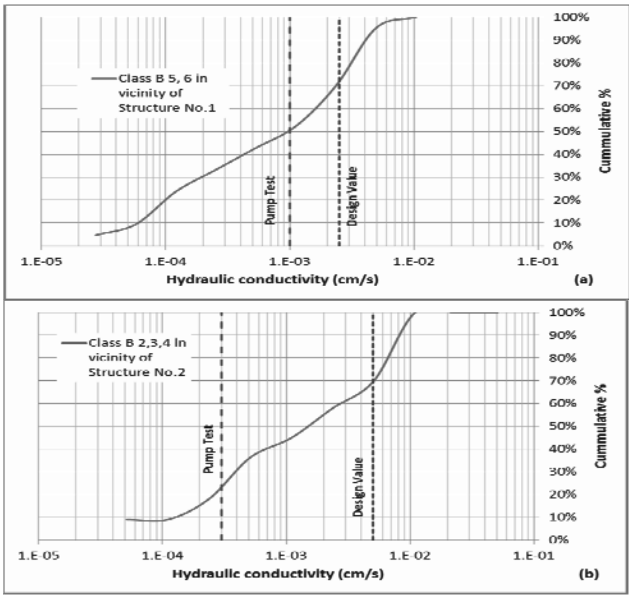

Figure 3 Localized distribution of hydraulic conductivity for (a) Class B5,6 in Structure No.1 and Class B2,3,4 Structure No.2.

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