FIELD MEASUREMENT OF HYDRAULIC CONDUCTIVITY IN A CLAYEY SAND DRUMLIN

Steven E. Poirier, Don J. DeGroot, and David W. Ostendorf, Department of Civil and Environmental Engineering, University of Massachusetts Amherst, Amherst, Massachusetts, USA

ABSTRACT
This paper presents results from field measurements of the hydraulic conductivity of a clayey sand drumlin located in eastern Massachusetts. The drumlin consists of a 30 m thick layer of dense, well-graded, weathered and unweathered till. Slug tests were conducted across a network of over 50 wells broadly distributed across the site and with depth. The hydraulic conductivity ranges almost 5 orders of magnitude from 10^{-08} to 10^{-03} cm/s. Values generally decrease with depth with about a two order of magnitude difference in the geometric mean of k values between the shallow weathered till and the deep unweathered till. The higher values in the weathered till are due to preferential flow paths, which were identified by test pits and dye infiltration tests. However, no horizontal spatial trends were evident within both the weathered and unweathered till in spite of the drumlin's topographic relief.

RÉSUMÉ
Cet article présente les résultats des mesures sur le terrain de la conductivité hydraulique d'un drumlin de sable argilé situé dans L'est du Massachusetts. Le drumlin se compose d'une couche épaisse de 30 m de till altéré et non altéré, dense et bien-évalué. Des essais de lingot ont été effectués à travers un réseau de plus de 50 puits largement distribués à travers l'emplacement et avec la profondeur. La conductivité hydraulique s'étend presque 5 ordres de grandeur de 10^{-08} à 10^{-03} cm/s. Les valeurs diminuent généralement avec la profondeur avec d'environ une différence deux orders de grandeur dans le moyen géométrique des teneurs dn k entre le till altéré et superficial et le till non altéré profound. Les valeurs plus élevées dans le till altéré sont dues aux chemins préférentiels d'écoulement, qui ont été identifiés par des puits de sondage et des essais d'infiltration de colorant. Cependant, aucune tendance spatiale horizontale n'était évidente dans même le till altéré et non altéré malgré le soulagement topographique du drumlin.

1. INTRODUCTION

Determination of the in situ hydraulic conductivity (k) is an important aspect of site characterization programs that involve monitoring the extent and fate of contaminated groundwater. Hydraulic conductivity can vary over many orders of magnitude and may be influenced by soil matrix properties (grain size distribution, density, macropores and other preferential flow paths, etc.) and fluid properties (viscosity, density, etc.). In the specific case of sites founded on well-graded tills, relatively low values of hydraulic conductivity are common. However, the values may vary several orders of magnitude depending on post depositional alteration of the till due to effects such as weathering, oxidation, organic growth, etc. These effects can develop preferential flow paths in what would otherwise be a low hydraulic conductivity soil. Reported values of hydraulic conductivity for glacial till range from about 10^{-09} to 10^{-03} cm/s, although a majority of the results found in the literature concern glacial tills of the North American Interior Plain region, which have relatively high clay contents and low relief.

Preferential flow paths, such as fractures and other macropores can increase in situ hydraulic conductivity significantly. Determining the spatial extent of preferential flow pathways allows a more accurate interpretation of hydraulic conductivity across a site, which is a necessary input to hydrogeologic investigations for water resource development and contaminate transport. As a result, site characterization programs must pay careful attention to sampling, monitoring well location and installation, and hydraulic conductivity test equipment, procedures, and data analysis.

For the specific case of drumlins, deposition (type and grain size distribution of the source material) and post deposition geologic history (primarily weathering) are key factors that influence hydraulic conductivity. Drumlins are typically smooth, elongated hills with an elliptical shape. They are the product of subglacial deformation; a deforming layer of till is transported beneath the glacier, which molds itself around subglacial obstacles such as bedrock bumps. The glacial till is deposited as ice melted along the bottom of the glacier, then molded and streamlined by the pressure of the over-passing mass.

Although extensive geosciences research has been performed on drumlin formation, relatively little work has been done on the engineering properties of drumlins. This paper focuses on the in situ measurement of hydraulic conductivity using slug tests at a clayey sand drumlin located in eastern Massachusetts. It describes the test site, basic geology, and methods of investigation. Results from slug and pump recovery tests conducted in monitoring wells are presented using several different data reduction methods. The results provide a database for hydrogeologic studies of similar tills and drumlins not currently available in the literature. Previous work conducted at the site includes an overview of salt contamination issues by Shelburne et al. (2000) and modeling the hydraulic response of the drumlin by Ostendorf et al. (2004).

2. SITE DESCRIPTION

Deposited during the Pleistocene glaciation, the entire drumlin is approximately 424,000 m^2. The long axis is approximately 1000 m, while the short axis is about 600 m long. The actual research site, depicted in Figure 1, is roughly 35,000 m^2 and relatively flat, although the ground surface slopes sharply beyond the northwest and southwest boundaries. The elevation of the site is approximately 53 m above mean sea level. The drumlin consists of a thick dense subglacial lodgement till consisting of a weathered brown till veneer overlying an unweathered gray till. Bedrock is a light grayish-pink granite, locally jointed competent rock unit. Intrusive dikes of mafic rocks are present and can have a larger number of fractures. Previous construction projects on the site resulted in fill of varying thickness being distributed around the site.

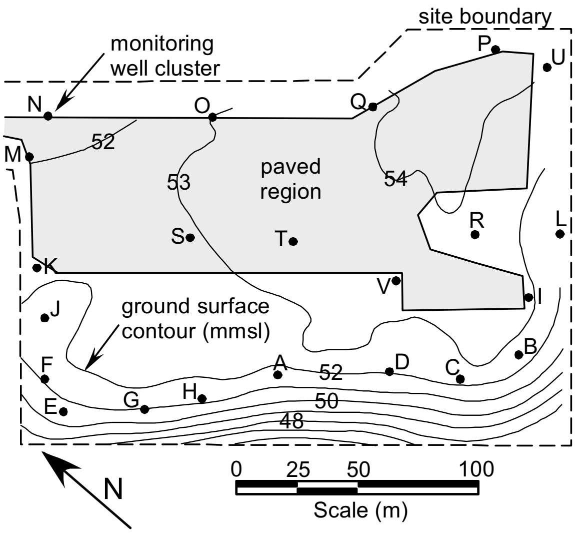

Figure 1. Site map with location of groundwater monitoring wells.

3. METHODS OF INVESTIGATION

3.1 Monitoring Well Installation

Groundwater monitoring well boreholes were advanced using either 10.8 cm inner diameter hollow stem augers or rotary drilling with a 9.8 or 14.9 cm roller bit. Standard Penetration Test split spoon samples were collected continuously for all deep monitoring wells that were drilled to bedrock. Samples were visually characterized on site and divided into several sections for moisture content, soil groundwater extract information, and grain-size distribution analysis in general accordance with the appropriate American Society for Testing and Materials (ASTM) standards. Blow counts, moisture contents, and boring log descriptions were later evaluated to get an indication of site stratigraphy.

Standard open standpipe monitoring wells constructed of Schedule 40 PVC pipe, 5.1 cm in diameter, were installed in the boreholes. Sections of slotted Schedule 40 PVC with 0.25 mm thick slots, 1.5 m in length, were used as screens. The hole was flushed with clean water prior to piezometer insertion. The screen was surrounded by a Morie sand filter pack extending 0.6 to 1 meter above the top of the screen. A 0.3 meter length bentonite chip seal was placed above the filter pack, and the remainder of the hole was sealed with a high solids content bentonite grout with a target mud weight of 1.2 g/cm^3. In shallow wells, bentonite chips were used in place of the grout whereas in deeper wells (> 10 m depth), bentonite chips were not used due to concerns of possible bridging, i.e., the grout was placed directly over the sand pack.

Wells were placed in clusters around the perimeter and center of the site as shown in Figure 1. Each cluster typically consists of four wells: one deep well to bedrock approximately 25 to 30 m below the ground surface, wells at approximately 12 m and 9 m below the ground surface, and shallow wells approximately 5 m below the ground surface. Some of the shallow wells were constructed with 3.1 m screen lengths to intercept the water table. In general, the bedrock and 12 m wells were located within the gray till, while the 9 m wells were in the brown till, and the shallow wells were across the fill/brown till interface.

3.2 Test Pits and Trenches for Dye Infiltration

Four test pits and two trenches were excavated in an effort to visualize the shallow fill/weathered till stratigraphy. Test Pit 1 and Trench 2 were used to inspect dye infiltration tests. Test pits were excavated using a backhoe and were approximately 2 square meters ranging in depth from 2 to 3 m.

To perform the dye infiltration tests, approximately 10 cm of the topsoil of a 1.5 m by 1.5 m plot was removed and the newly exposed surface flattened. A square trench, nominally 1 m per side, was dug to a depth of approximately 15 cm. A 112 cm square, 60 cm deep, 0.3 cm thick stainless steel infiltration ring was placed in the trench. Bentonite chips were used to seal the perimeter of the ring and tarps were used to minimize evaporation. A water/dye solution was mixed using Brilliant Blue FCF (FD&C Blue No. 1) to a concentration of approximately 4.7 g/L. Approximately 120 liters of solution was poured into the ring and allowed to pond. This volume corresponds to a moderately heavy rainfall depth of about 8.5 cm at the site based on rain gauge data.

All of the solution infiltrated into the ground overnight. Thereafter the ring was removed, and a test pit or trench was excavated approximately 20 cm from the edge of the test area using a backhoe. With hand tools, the wall of the rough excavation facing to the dye infiltration test was trimmed to the edge of the test area. Once the face of the pit or trench was vertical and as smooth as possible, photographs were taken. The vertical face was sequentially trimmed and photographed in 10 cm increments.

3.3 Slug and Pump Recovery Tests

Slug tests and pump recovery tests were performed to determine hydraulic conductivity in general accordance with ASTM D4044 Standard Test Method *(Field Procedure) for Instantaneous Change in Head (Slug Tests) for Determining Hydraulic Properties of Aquifers*. Data from the slug and pump recovery tests were recorded with pressure transducers and dataloggers. Manual readings were first recorded in the target wells and compared to historic readings to ensure nominal hydraulic equilibrium. Slug tests were performed with solid aluminum 3.8 cm diameter rods, nominally 1 or 2 meters in length. A "draw-up" test (i.e., flow out of the well) was first conducted by quickly lowering the slug into the well. Data readings were typically recorded at a frequency of every 5 seconds for the first 30 minutes and then switched to about every 15 minutes thereafter. The well water level was allowed to come back to at least 90 to 95% equilibrium after the slug insertion before ending the test. Upon completion of the draw-up test, the data were downloaded to a PC laptop and the data acquisition was re-initiated for removal of the slug, i.e., a "draw-down" test – flow into the well. Typical recovery periods ranged from a several hours to a few days.

Pump recovery tests were conducted in conjunction with groundwater sampling events. In accordance to traditional monitoring well sampling procedures, approximately three well volumes were purged before water sampling and pump recovery monitoring. Because of the relatively low hydraulic conductivity of the till, most wells went "dry" during pumping, thus the pump recovery tests involved a significantly larger volume of water than the slug tests, particularly for the deep wells. Pressure transducer readings were typically recorded once every 2 hours. In many cases it took a few days up to a couple of weeks before full recovery was achieved.

4. PRESENTATION OF RESULTS

4.1 Site and Soil Characteristics

N-values from Standard Penetration Tests typically range from 50 to 100 blows and show little variation with depth or location. Since boulders and cobbles are widespread throughout the till, refusal during split spoon sampling was common. Large jumps in moisture content generally occur near the fill/till interface due to a buried organic layer, while the moisture content of the till is typically below 15%.

The brown and gray till show similar grain-size distributions (Figure 2). Typical average percentages for the SPT samples are: 17% gravel (75 to 4.75 mm), 39% sand (4.75 to 0.075 mm), 33% silt (0.075 mm to 0.002 mm), and 11% clay (< 0.002 mm). Variation with depth is minimal, although often a slight increase in clay content is found directly above the bedrock. A majority of the samples comprise greater than 50% coarse material, classifying the soil as a coarse-grained soil using the Unified Soil Classification System (USCS). Typical grain-size distribution curves are nearly linear in semi-log space, suggesting the soil in situ is in a highly dense condition. All samples have coefficients of uniformity greater than 9.

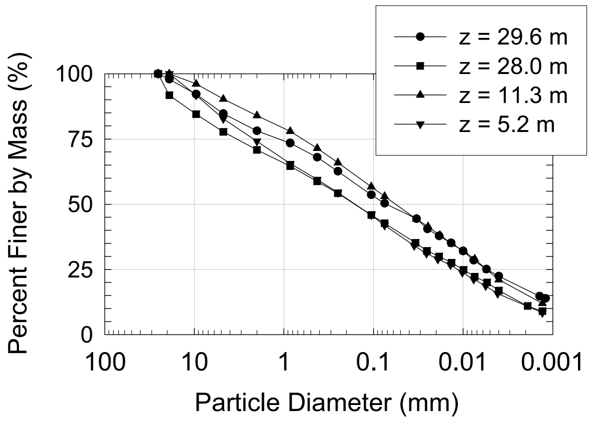

Figure 2. Typical grain size distribution curves for weathered and unweathered till from SPT samples.

Atterberg limits all plot above the A-line in the CL or CL-ML range of a Casagrande plasticity chart, indicating the fines are low plastic, inorganic clays; sandy and silty clays or silty clays; or clayey silts and sands. Liquid limits range from 19 to 26% and plasticity index ranges from 6 to 12%. In all cases, the natural water content is less than the plastic limit with an average liquidity index equal to -0.4. The activity of the fine particles ranges from 0.53 to 0.97 with an average of 0.6, indicating inactive clay. Based on the results of the grain size analysis and the Atterberg limits, the USCS classification of the soil is SC-CL.

Figure 3 plots a summary of the SPT and classification data for well cluster A (see location in Figure 1). These data are typical for all the well clusters on site with the exception that there are some differences of a few meters among the cluster locations in the thickness of the fill and weathered brown till layers. There is little variation among the grain-size distribution curves and other soil index tests with depth or location, indicating that the weathered and unweathered tills are of the same depositional unit.

4.2 Test Pits and Dye Infiltration

Based on the boring logs and visual observation in test pits and trenches, the fill is a rocky, well-graded material 1 to 5 m thick. This layer generally increases in thickness towards the southwest region of the site, i.e., away from the drumlin's centroid. A thin dark, highly oxidized organic layer below the fill marks the original ground surface.

Roots are ubiquitous in the upper portion of the fill and decrease with depth to the original ground surface, where relic roots are present. Beneath the organic layer is a rocky, oxidized brown till with many roots followed by a second less rocky brown till layer that contains occasional vertical hydration zones. These zones generally have an outer rim with orange/red, highly oxidized material surrounding an inner, gray core of reduced oxidized material. The reduced oxidized cores are on the order of 2.5 cm thick, and the highly oxidized material approximately 0.3 cm thick. There is no apparent spatial pattern among the vertical hydration zones. The transition zone between the brown weathered till and gray unweathered till was visible in a couple of the test pits. This zone is mottled and contains some vertical hydraulic features that are similar in size and color to those found in the brown till.

The results of the dye infiltration tests prove the existence of permeability continuums in the fill and brown till layer. Evidence of dye extended up to several meters from the infiltration tests, and in all instances beyond the depth of excavation. The tests show infiltration is fairly uniform at the ground surface, due to the numerous roots. Beneath this upper root zone, the infiltration becomes increasingly preferential down to the original ground surface, where infiltration is again fairly uniform. Thereafter the infiltration becomes increasingly preferential with depth where flow followed individual roots and the highly oxidized vertical hydration zones.

Although index and classification data (Figure 3) suggest a uniform soil deposit across the site, it is clear from the test pits and dye infiltration tests that macrofeatures are present at shallow depths. These features undoubtedly have a significant influence on measurements of hydraulic conductivity in shallow wells founded in the fill/weathered brown till versus the deeper unweathered gray till.

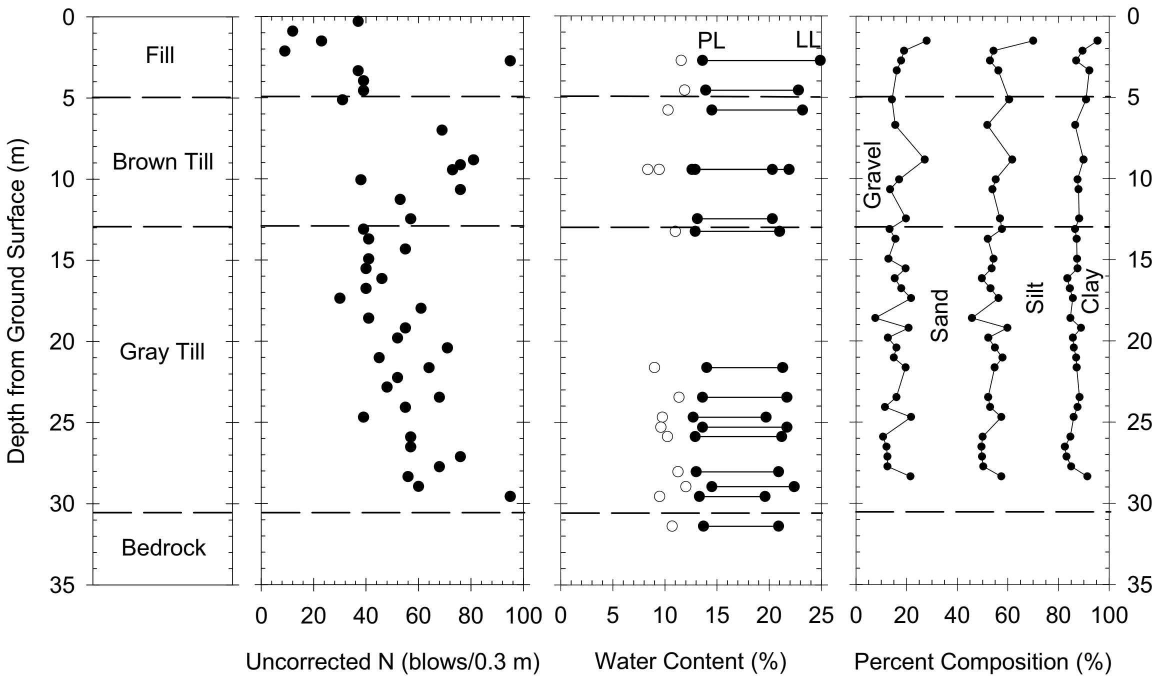

Figure 3. SPT and Classification data for Well Cluster A (Atterberg Limits are a composite from several well clusters).

4.3 Slug and Recovery Tests

Slug and pump recovery tests were reduced using three popular reduction techniques: Hvorslev (1951), Bouwer and Rice (1976), and Cooper et al. (1967).

Hvorslev (1951)

For Hvorslev's method, the hydraulic conductivity was computed as:

$$k_H = -2.3am_{HV}/F \quad [1]$$

using Chapius' (1989) shape factor

$$F = (2\pi L_e)/(\ln[(L_e/D)+(1+(L_e/D)^2)^{0.5}]) - 2.75D \quad [2]$$

where:

k_H = horizontal hydraulic conductivity (cm/s)
a = area of monitoring well (cm^2)
m_{HV} = initial slope of log draw-up/down vs. time plot (1/s)
F = shape factor, function of well geometry (cm)
L_e = length of filter pack (cm)
D = diameter of filter pack (cm)

Filter pack lengths and diameters varied although the most common length was 2.1 m with a diameter of either 9.8 or 14.7 cm.

Bouwer and Rice (1976)
For Bouwer and Rice's method the hydraulic conductivity was computed as:

$$k_H = [r_c^2 \ln(R_e/r_w)/(2L)]\ m_{BR} \quad [3]$$

$$\ln(R_e/r_w) = [\{1.1/\ln(L_w/R_w)\}+\{A+B \ln((b-L_w)/r_w)\}/(L/L_w)]^{-1} \quad [4]$$

where:
k_H = horizontal hydraulic conductivity (cm/s)
r_c = well radius (cm)
R_e = effective radius (cm)
r_w = radius of filter pack (cm)
L = length of screen (cm)
L_e = length of filter pack (cm)
m_{BR} = slope of log head vs. time plot (1/s)
L_w = depth from the water table to well bottom (cm)
A, B, C = coefficients
b = aquifer thickness (cm)

The coefficients A, B, and C are dependent on well geometry. Typical dimensions were, screen lengths of either 1.5 or 3.1 m, well radii of 5.1 cm, and aquifer thicknesses around 30 m. Values ranged from 1.8 to 3.1 for A, 0.25 to 0.5 for B, and 1.1 to 2.8 for C. Conductivities were calculated considering partial well penetration.

Cooper et al. (1967)
The Cooper et al. method is also described in ASTM D4104 *(Analytical Procedure) for Determining Transmissivity of Nonleaky Confined Aquifers by Overdamped Well Response to Instantaneous Change in Head (Slug Test)*. The draw-up/down response was normalized by the initial head displacement and plotted vs. the logarithm of the time. The data plot was overlain by a type-curve plot prepared on graph paper of the same format (same number of log cycles). The type curves were matched to the plot of the field data. Match points were selected from each plot. An estimate for the radial component of hydraulic conductivity was calculated from the definition:

$$K_H = T / b \quad [5]$$

$$T = (T\ t_c / r_c^2)(r_c^2 / t_c) \quad [6]$$

where:
K_H = horizontal hydraulic conductivity (cm/s)
T = transmissivity (cm^2/s)
b = aquifer thickness (cm)
Tt_C/r_c^2 = match point from Cooper curve
r_c = well radius (cm)
t_C = match point time (s)

Slug Test Results
Calculated k values from the three reduction methods showed a log normal distribution with values ranging from 10^{-08} to 10^{-03} cm/s. The geometric means were computed as

$$k_{gm}=e^{(\Sigma \ln(k)/N)} \quad [7]$$

where:

k_{gm} = geometric mean hydraulic conductivity (cm/s)
k = hydraulic conductivity (cm/s)
N = number of tests

Taking all wells together, the resulting geometric means are 8×10^{-06} cm/s for Hvorslev, 1×10^{-05} cm/s for Bouwer and Rice, and about 7×10^{-07} cm/s for Cooper et al.

In general, the draw-up slug tests produce slightly greater k values than the draw-down tests (Figure 4), but overall the difference is not significant.

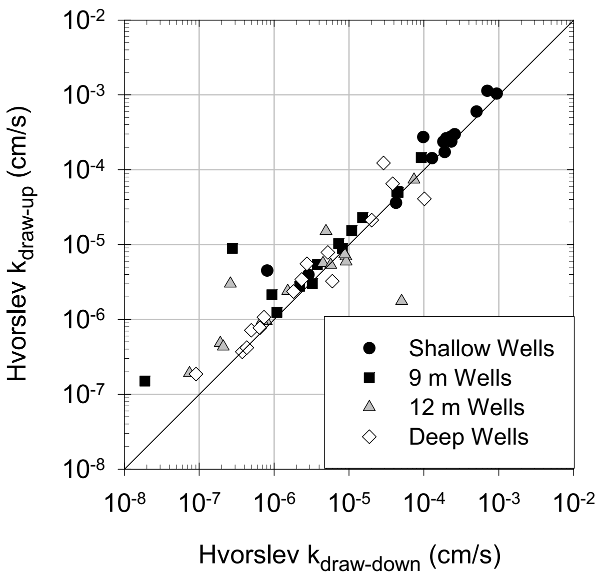

Figure 4. Comparison of k values determined from draw-up versus draw-down slug tests – Hvorslev (1951) method of data reduction.

Estimates of k using Hvorslev or Bouwer and Rice methods of analysis are approximately equal as shown in Figure 5. However, there are significant differences between these two methods and k values computed using Cooper et al. The differences are about one order of magnitude as shown in Figure 6, with the Cooper et al. method producing lower values. This difference is presumably due to the fact that the Cooper et al. assumptions of a confined aquifer and fully penetrating well are violated for the drumlin site. Herzog (1994) also found large differences for slug tests conducted in a till and a sand deposit, except that the Cooper et al. analysis produced larger values than Hvorslev and Bouwer and Rice analysis. This is unlike that found for the drumlin site for which the Cooper et al. values were smaller.

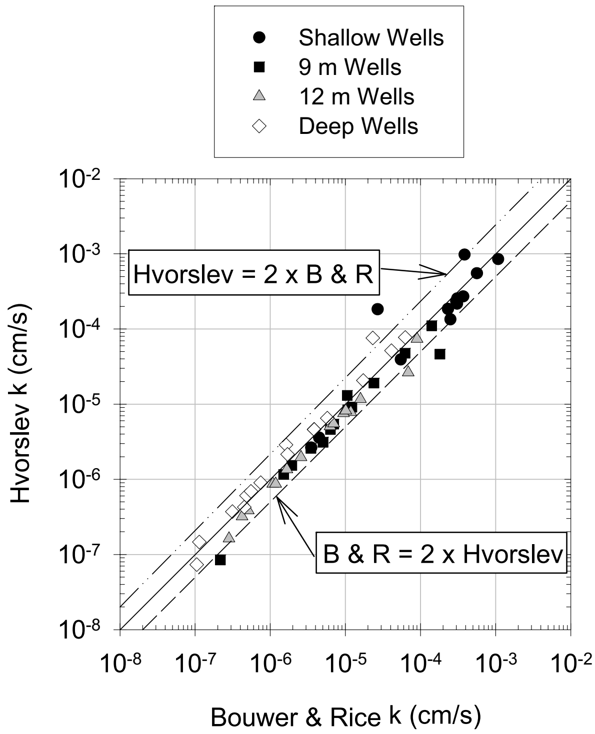

Figure 5. Comparison of Hvorslev and Bouwer and Rice data reduction methods.

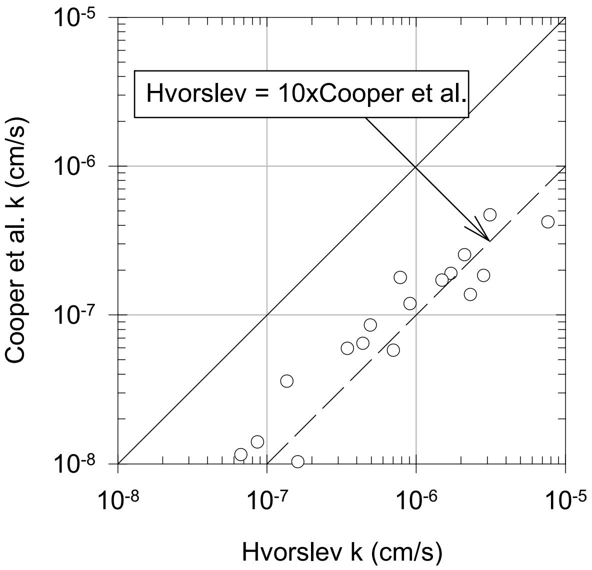

Figure 6. Comparison of Hvorslev and Cooper et al. data reduction methods.

Figure 7 plots k values by well depth for the site and the best-fit log-normal distributions. The data in this figure were compiled by computing the geometric mean of k values based on multiple tests conducted for each well analysed using the Hvorslev and Bouwer and Rice methods. No Cooper et al. values were used to compute the data in Figure 7. The k values range between 10^{-8} to 10^{-3} cm/s with an overall geometric mean equal to 10^{-5} cm/s. With well depth, the geometric means are $1x10^{-04}$, $8x10^{-06}$, $4x10^{-06}$, and $2x10^{-06}$ cm/s for shallow, 9m, 12 m, and deep wells, respectively. The greatest difference is between the shallow wells and all wells at other depths. This result is expected since the shallow wells are primarily in the fill and/or weathered brown till layer versus the deeper wells being founded in the unweathered till.

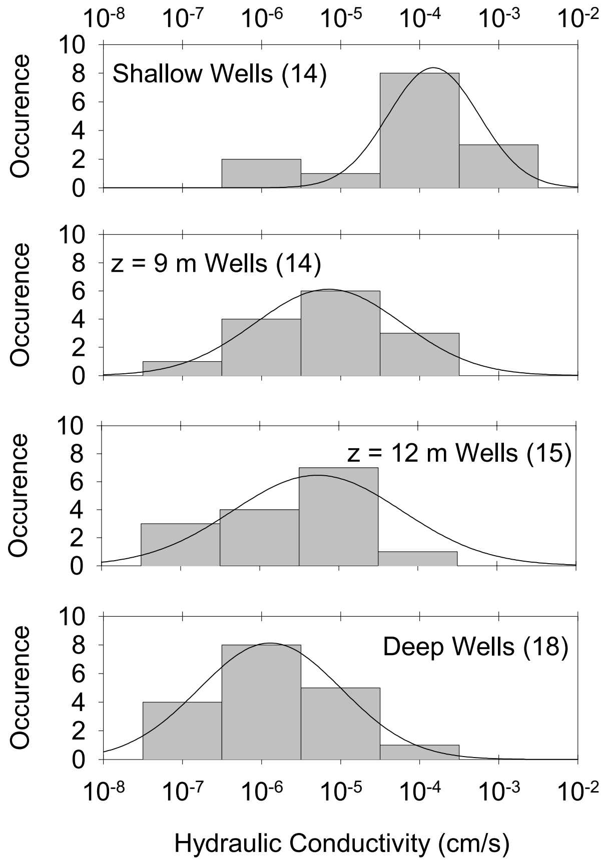

Figure 7. Distribution of k values by well depth.

The overall range of k values is consistent with that reported by others for weathered and unweathered tills (e.g., D'Astous et al. 1989, Gerber and Howard 2000). While clear differences between the weathered and unweathered tills were expected, the range of values within the unweathered till is larger than expected. It is evident that the index and classification data, such as that presented in Figure 3 and which did not vary across the site suggesting a "uniform" deposit, did not indicate features that must be influencing the unweathered till in situ k values. While preferential flow paths were evident in the shallow weathered till based on the test pits and dye infiltration tests, there must also be preferential, albeit smaller, flow paths in the unweathered till. These could be such features as boulder fields, sand layers and lenses, and shear planes.

Pump Recovery Tests
Hydraulic conductivity values determined from the pump recovery tests were generally lower but within one order of magnitude of the k values determined from the much smaller volume slug tests. Generally the opposite is found for k values based on steady pumping tests due to scale effects as noted, for example, by Butler and Healey (1998). The reason for the lower k values measured at the drumlin site is most likely because each well in a cluster was pumped dry over three consecutive days due to the ground water sampling protocol. Overlapping cones of depressions within a cluster of wells influenced the recovery process. Each well within the cluster, despite being at different depth, acted as a negative boundary on the other cluster wells. Therefore, all wells within a cluster are competing for recovery from the same stored groundwater, resulting in underestimation of k from recovery data.

Long Term Time Effects
Slug tests were repeated over a 4-year span in a single well (Cluster O at depth = 9 m) to determine the long term effects, if any, of the pumping process. Figure 8 plots the results and shows no apparent trend over time. These results are reassuring in that they show good consistency in test procedures and measured k values. Furthermore, they indicate that the process of pumping the wells dry during monthly groundwater sampling events has no effect on k – despite the large gradients that this process induces in the wells.

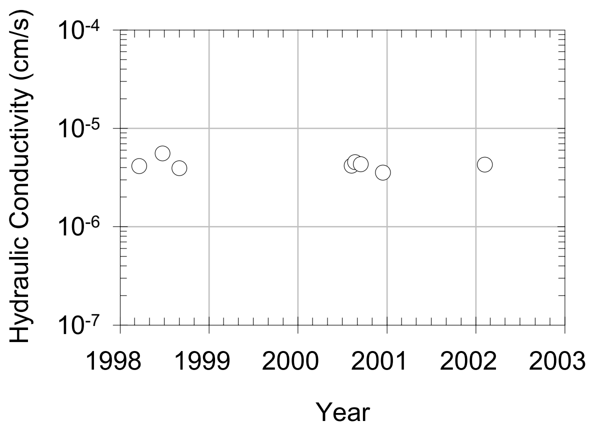

Figure 8. Slug tests conducted over a four year period in Cluster O - 9 m depth well (data for draw-down tests with Hvorslev analysis).

5. CONCLUSIONS

The large number of wells and slug tests performed at the drumlin test site provided an opportunity to analyze trends in k values due to factors such as: 1) interpretation method (Hvorslev, Bouwer and Rice, and Cooper et al.); 2) test method (draw-up vs. draw-down); 3) small volume slug tests versus large volume recovery tests, 4) long term effects of well pumping; 5) landform (drumlin vs. low relief), and 6) till characteristics (weathered vs. unweathered till and macrofeatures).

Hydraulic conductivity values estimated using the Hvorslev and Bouwer and Rice methods were approximately equal. The Cooper et al. method gave values about one order of magnitude less, presumably due to the violation of the Cooper et al. assumptions of a confined aquifer and a fully penetrating well for the drumlin site and well configurations. No significant differences were found between k values determined from draw-up versus draw-down tests. However, large volume pump recovery tests gave lower k values than the small volume slug tests which is presumed to be due to well interference within each cluster. No variation in k values were observed over a four year period of conducting repeat slug tests in a single well.

Overall, the k values range over almost 5 orders of magnitude from 10^{-08} to 10^{-03} cm/s following a log normal distribution. Values generally increase with depth but no horizontal spatial trends are evident. The largest difference in k is between the weathered and deep unweathered tills with close to two orders of magnitude difference in k values (≈ 1×10^{-4} vs. 2×10^{-6} cm/s). Marcofeatures that were visible in the test pits and dye infiltration tests are largely responsible for this difference. However, even within the unweathered till the range in k values was large (3 orders of magnitude). This suggests that there must also be randomly distributed preferential flow paths such as boulder fields, sand layers, and shear planes in the unweathered till. None of these potential features were indicated by any of the classification and index testing (water content, Atterberg Limits, grain size distribution, and SPT N values) which all suggested the site consisted of a uniform till layer.

6. ACKNOWLEDGEMENTS

This work described herein was conducted as part of a research project sponsored by the Massachusetts Highway Department (MHD). The authors thank the MHD for this funding and for field support on the site. The views, opinions, and findings contained in this paper are those of the Authors and do not necessarily reflect Massachusetts Highway Department official views or policies. This paper does not constitute a standard, specification, or regulation.

7. REFERENCES

D'Astous, A.Y., Ruland, W.W., Bruce, J.R.G., Cherry, J.A., and Gillham, R.W. 1989. Fracture effects in the shallow groundwater zone in weathered Sarnia clay. Canadian Geotechnical Journal, 26: 43-56.

Bouwer, H. and Rice, R.C. 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. *Water Resources Research*, (12)3: 423-428.

Butler, J.J., Jr. and Healey, J.M. 1998. Relationship between pumping-test and slug-test parameters: scale effect or artifact? Groundwater, 36(2): 305-313.

Chapius, R.P. 1989. Shape factors for permeability tests in boreholes and piezometers. *Ground Water*, 27(5): 647-654.

Cooper, H.H, Bredehoeft, J.D., and Papadopulos, I.S. 1967. Response of a finite-diameter well to an instantaneous charge of water. *Water Resources Research*, 3(1): 263-269.

Gerber, R.E. and Howard, K.W.F. 2000. Recharge through a regional aquitard: three-dimensional flow model water balance approach. Groundwater 38: 410-422.

Herzog, B.L. 1994. Slug tests for determining hydraulic conductivity of natural geologic deposits. Hydraulic Conductivity and Waste Contaminant Transport in Soil, ASTM STP 1142, Daniel, D.E. and Trautwein, S.J., Eds., ASTM, Philadelphia, 95-110.

Hvorslev, M.J. 1951. Time lag and soil permeability in groundwater observations. *U.S. Army Corps of Engineers Waterways Experiment Station Bulletin 36*.

Ostendorf, D.W., DeGroot, D.J., Shelburne, W.M., and Mitchell, T.J. 2004. Hydraulic head in clayey sand till over multiple time scales. Canadian Geotechnical Journal, 41(1): 89-105.

Shelburne, W.M., Poirier, S.E., and DeGroot, D.J. (2000). Hydrogeology of a drumlin with application to road salt contamination. Proc. of the 53th Canadian Geotechnical Engineering Conference, 197-204.