

Comparison of Different Field Test Methods to Assess Hydraulic Conductivity

Hugh Gillen & Sonny Sundaram
Englobe Corp., Ottawa, Ontario, Canada
Kevin Bailey
Englobe Corp., Kitchener, Ontario, Canada



ABSTRACT

Hydraulic conductivity of geological materials is a key parameter in the evaluation of groundwater aquifers. Different field test methods were used to assess hydraulic conductivity. The groundwater response to these tests was evaluated by applying the analytical solution by Bouwer and Rice (1976) to estimate the hydraulic conductivity values. A constant rate pumping test was also conducted and evaluated using the Theis (1935) solution to estimate hydraulic conductivity.

The measurements of hydraulic conductivity were analyzed using statistical techniques to identify correlations in the data. We also compared the hydraulic conductivity results to evaluate the effect of soil material heterogeneity on the estimated range of hydraulic conductivity values. The study helped to identify the pros and cons of each field test method and yielded recommendations for the selection of appropriate field test methods depending on the end-use.

RÉSUMÉ

La conductivité hydraulique des matériaux géologiques est un paramètre clé pour la caractérisation des aquifères d'eaux souterraines. Différentes méthodes d'essai ont été utilisées pour évaluer la conductivité hydraulique. La réponse de l'eau souterraine à ces tests a été évaluée en appliquant la solution analytique de Bouwer et Rice (1976) pour estimer les valeurs de conductivité hydraulique. Un essai de pompage à débit constant a également été effectué et évalué à l'aide de la solution de Theis (1935) pour estimer la conductivité hydraulique.

Les mesures de la conductivité hydraulique ont été analysées à l'aide de techniques statistiques pour identifier les corrélations dans les données. Nous avons également comparé les résultats de conductivité hydraulique pour évaluer l'effet de l'hétérogénéité des matériaux du sol sur la variation des valeurs de conductivité hydraulique. L'étude a permis d'identifier les avantages et les inconvénients de chaque méthode d'essai et a produit des recommandations pour la sélection de méthodes d'essai approprié en fonction de l'utilisation finale.

1 INTRODUCTION

Hydraulic conductivity of geological materials is a key parameter in the evaluation of water flow within groundwater aquifers. Hydraulic conductivity is useful in a wide variety of geological and engineering applications, such as water quantity estimates for water supply wells, estimating dewatering requirements for construction dewatering scenarios, and in the evaluation of fate and transport of contaminants present at contaminated site, among many other applications.

Owing to its importance, a variety of field test methods (i.e., pumping tests, slug tests, and constant-head tests) have been developed to estimate hydraulic conductivity. Additionally, many empirical relations have also been developed to estimate hydraulic conductivity from more easily measurable soil properties (i.e., grain size distributions). Of the three overarching in-situ hydraulic conductivity field methods above, slug tests are typically the simplest and least costly method to implement. As a result, many evaluations are completed exclusively through the use of slug test methods. However, each test method will have its own pros and cons, as well as its own data quality and reliability depending on aquifer conditions and test well construction. It is not always clear to practitioners which hydraulic conductivity test method to

implement on a project, given location-specific aquifer properties, well construction, budget, and/or site access.

The purpose of this study was to compare a selection of these different field test methods and empirical relations to evaluate differences between the estimated hydraulic conductivity values, if any. The findings of this study were expected to aid practitioners with the selection of appropriate methods to suit site-specific conditions and/or compensate for the use of alternate methods when impractical to adopt the preferred method.

1.1 Test Site Description

All testing conducted for this study was conducted at a single site with a relatively uniform unconfined sand aquifer. The site was undeveloped, with no existing water taking or other significant groundwater interferences identified within the anticipated radius of influence of the field tests that were performed. The fast recovery and relatively consistent subsurface conditions permitted comparison of different field test methods over multiple test locations at the site and within a short period of time.

2 STUDY SETUP

2.1 Drilling and Sampling Program

The subsurface conditions at the site were characterized using five boreholes advanced to depths ranging from 6.1 to 12.2 mbgs. The boreholes were advanced using a sonic drill rig with a 150-mm outside diameter drill bit.

Representative soil samples were collected from within each borehole. All collected soil samples were logged in the field for texture, moisture, and visual appearance. Soil samples were obtained using a direct push sampling sleeve advanced by the sonic drill rig at continuous 1.52-m intervals.

2.2 Test Wells

The five boreholes were each instrumented as monitoring wells upon the completion of drilling. The monitoring wells were designated as MW22-01A, MW22-01B, MW22-02, MW22-03, and MW22-04. The monitoring wells at MW22-01A (shallow) and MW22-01B (deep) were clustered approximately 1.5 m apart. The remaining monitoring wells were installed approximately 100 to 120 m apart.

Five wellpoints were also installed, in a straight line at offset distances of 2.4 m (MWP 1), 7.9 m (MWP 2), 14.9 m (MWP 3), and 27.6 m (MWP 4) from the first wellpoint (PWP). The wellpoints were centrally located within the triangular area between MW22-01A/B, MW22-02, and MW22-04. The relative locations of the monitoring wells and wellpoints are depicted approximately in Figure 1.



Figure 1. Layout of monitoring wells and wellpoints

The five monitoring wells were constructed using Schedule 40, 50.8-mm diameter polyvinyl chloride (PVC) casings with a 0.254-mm machine-slotted screen. The well screen pipes were 1.5 m long and installed with an appropriate length of solid PVC riser pipe with threaded joint connections extending to grade. A sand pack consisting of clean silica sand was then placed within the annulus space surrounding the screened section of the wells and to a depth of approximately 0.3 m above the top of the well screen. Bentonite hole plug was placed below the screened interval as well as from the top of the sand layer to within approximately 0.6 m of the surface to hydraulically isolate the well screen interval. The

monitoring well installation depths and elevations are summarized in Table 3.

Following installation and before any testing, all monitoring wells were developed by removing water until a visually clear state was achieved.

Table 3. Well installation details

Monitoring well ID	Surface elevation (masl)	Well screen interval	
		Depth (mbgs)	Elevation (masl)
MW22-01A	242.70	3.76 – 5.28	237.42 – 238.94
MW22-01B	242.66	6.47 – 7.99	234.67 – 236.19
MW22-02	242.18	3.70 – 5.22	236.96 – 238.48
MW22-03	242.19	3.58 – 5.10	237.09 – 238.61
MW22-04	242.68	4.75 – 6.27	236.41 – 237.93

The five wellpoints were installed to approximately 6 mbgs via jetting, to assist with the completion of a constant rate pump test. Each wellpoint consisted of a 32-mm diameter PVC wellpoint with a 0.45-m long screen.

3 SITE CHARACTERIZATION

3.1 Site-Specific Stratigraphy and Regional Setting

The site stratigraphy consisted of a sand to silty sand deposit encountered at each of the five boreholes advanced for this study. The sand deposit was brown and generally contained trace silt and trace clay but was silty at MW22-04. The sand deposit was identified down to approximately 6.1 to 9.2 metres below ground surface (mbgs). A deposit of silty clay was encountered in MW22-01B from approximately 9.2 to 12.2 mbgs and was assumed to represent the bottom of the unconfined aquifer at the site.

Five grainsize distribution tests by sieve and hydrometer were conducted on selected soil samples retrieved from depths corresponding to the well screen intervals. The results of the grainsize distribution tests are summarized in Table 1.

Table 1. Grainsize distribution test results

Sample Location	% Gravel	% Sand	% Silt	% Clay
MW22-01B (6.8 – 7.6 mbgs)	0.0	95.8	3.6	0.6
MW22-02 (3.8 – 4.6 mbgs)	0.7	92.0	4.5	2.8
MW22-03 (3.8 – 4.6 mbgs)	0.0	97.1	0.9	2.0
MW22-04 (5.3 – 6.1 mbgs)	0.2	71.2	20.7	7.9

Publicly available information for the site was also briefly reviewed, including databases published by the Ontario Geological Survey (OGS), the Ministry of the Environment, Conservation and Park (MECP) water well records, and the Ministry of Northern Development and Mines (MNDM). Based on this review, the regional geological setting for the area of the site generally comprises glaciolacustrine deposits of sand, gravel, and minor silt and clay. This regional geological setting is consistent with the site-specific stratigraphy that was identified in the boreholes and grainsize distribution test results.

The surficial soil deposits identified above are understood to be associated with the Norfolk Sand Plain physiographic region. The bedrock geology consists of limestone, dolostone, and shale of Detroit River Group from the Onondaga Formation (Ontario Geological Survey, 2011). Bedrock was not encountered within the depth investigated for this study, as expected.

3.2 Static Groundwater Level Measurements

The depth to groundwater was measured in each of the boreholes as drilling progressed and upon completion, on March 7 and 8, 2022. The depth to groundwater was then measured again in all newly installed wells at the site on March 8, March 10, and March 16, 2022. The groundwater level measurements are summarized in Table 2.

Table 2. Measured water levels

Monitoring well ID	Groundwater depths (mbgs) / elevations (masl)		
	Mar. 8, 2022*	Mar. 10, 2022	Mar. 16, 2022
MW22-01A	3.54 / 239.16	3.56 / 239.14	3.57 / 239.13
MW22-01B	3.46 / 239.20	3.52 / 239.14	3.54 / 239.13
MW22-02	2.30 / 239.88	2.30 / 239.88	2.35 / 239.83
MW22-03	2.48 / 239.71	2.49 / 239.70	2.53 / 239.66
MW22-04	3.47 / 239.21	3.43 / 239.25	3.44 / 239.25

masl: metres above sea level

* Water levels observed immediately after the completion of drilling

4 FIELD TEST METHODOLOGY

Factors influencing hydraulic conductivity include particle shape, tortuosity, pore size distribution, and the viscosity and specific weight of the fluid (Freeze and Cherry, 1979). The testing for this study was conducted within a relatively consistent sand deposit, as shown by the gradation test results, on March 16, 18, and 22, 2022. It was assumed the viscosity and specific weight of the groundwater was constant over the short span of time over which the testing was conducted.

The field testing for this study involved conducting different single well response tests on the installed monitoring wells and conducting a constant rate pumping test using the jetted wellpoints.

4.1 Constant Rate Pumping Test

A constant rate pumping test was conducted using the five wellpoints at the site on March 22, 2022. The pumping test involved pumping with a centrifugal pump at a constant rate of approximately 60 litres per minute from one of the wellpoints (designated PWP) for approximately five (5) hours. The constant flowrate was monitored during the test using a digital GPI TM-200 in-line flowmeter with instantaneous and totalizing functions and manually checked periodically by measuring volumes of water effluent over a specified time interval. Water level measurements were obtained from the four other wellpoints, designated MWP 1 through MWP 4, over the duration of the test.

Water level measurements were obtained electronically from the pumping wellpoint and MWP 1 and MWP 2, and manually from MWP 1 through MWP 4. Barometric measurements were collected and used for atmospheric compensation of the datalogger data from MWP 1 and MWP 2. The time- and distance-drawdown results were used to estimate hydraulic conductivity.

4.2 Single Well Response Tests

Falling head and rising head single-well response hydraulic conductivity tests ("K-tests") were used to estimate the in-situ horizontal hydraulic conductivity at the Site for the geological materials intercepted at the well screens of MW22-01A, MW22-01B, and MW22-03 on March 16, 2022, and MW22-01B, MW22-02 and MW22-04 on March 18, 2022.

The single-well response K-tests were performed using several methods, including the insertion and removal of a solid slug of known volume, the insertion of a hydraulic slug of known volume, and short duration recovery using a submersible pump.

Solid slug tests were performed by inserting a solid slug into the well and recording the water level as it receded (falling head). The solid slug was then removed, and the water level was recorded again as it recovered (rising head).

Hydraulic slug tests were performed by increasing the groundwater level by near-instantaneously introducing a known water volume into the monitoring well and measuring the subsequent groundwater response. A large funnel with a stopper was used to facilitate the hydraulic slug tests.

Short duration recovery testing was performed by reducing the groundwater level in the well using a submersible pump positioned just above the well screen, then turning off the pump and measuring the subsequent groundwater response. A check valve was used with the submersible pump to prevent flowback of water from the pump to the well when turning off the pump. Only one short duration recovery test could be completed due to the submersible pump becoming clogged by very fine sand.

Water levels were recorded both electronically with a datalogger and manually with a water level probe during the recovery phases of the K-tests.

5 TEST RESULTS AND DISCUSSION

A total of twenty-one single well response tests (SWRTs) and one constant rate pumping test were conducted for this study. The SWRTs consisted of fourteen solid slug tests (falling head and rising head), six hydraulic slug tests (falling head), and one short duration recovery test (rising head). Hydraulic conductivity was also estimated using the results from five grain size distribution tests.

5.1 Estimation of Hydraulic Conductivity

The field test results were analyzed with the aid of AQTESOLV for Windows, Version 4.50.002. Hydraulic conductivity was estimated from the SWRT data using the Bouwer-Rice (1976) solution for a partially penetrating well in an unconfined aquifer. The constant rate pumping test data was analyzed using the Theis (1935) solution.

In addition to the hydraulic conductivity estimates from the field test data, hydraulic conductivity was estimated using the grain size distribution curves for the five tests summarized in Table 1. The grain size distribution data was analyzed using the HydrogeoSieveXL tool developed by Devlin (2015), which produced estimates of hydraulic conductivity using up to fifteen selected empirical relationships. Only the hydraulic conductivity estimates determined using models for which the applicable criteria were met were considered. The geometric mean of the admissible estimates was then selected as the final estimation of hydraulic conductivity for a given grain size distribution dataset.

The estimated hydraulic conductivity from each of the completed tests are summarized in Table 4.

Table 4. Estimated hydraulic conductivity

Test location	Test method	Hydraulic conductivity (m/s)
MW22-01A	Hydraulic slug, falling head	2.05×10^{-4}
	Solid slug, falling head	1.87×10^{-4}
	Solid slug, rising head	2.11×10^{-4}
	Hydraulic slug, falling head	1.97×10^{-4}
MW22-01B	Short duration recovery test, rising head	2.42×10^{-4}
	Hydraulic slug, falling head	2.17×10^{-5}
	Solid slug, falling head	1.98×10^{-4}
	Solid slug, rising head	2.19×10^{-4}
	Grainsize distribution data	1.49×10^{-4}
MW22-02	Solid slug, falling head	2.97×10^{-4}
	Solid slug, rising head	3.33×10^{-4}
	Hydraulic slug, falling head	2.72×10^{-4}
	Grainsize distribution data	1.03×10^{-4}
MW22-03	Solid slug, falling head	1.95×10^{-4}
	Solid slug, rising head	1.30×10^{-4}
	Hydraulic slug, falling head	1.93×10^{-4}
	Grainsize distribution data	1.58×10^{-4}
MW22-04	Solid slug, falling head	3.02×10^{-4}
	Solid slug, rising head	3.40×10^{-4}

	Hydraulic slug, falling head	1.94×10^{-4}
	Solid slug, falling head	2.51×10^{-4}
	Solid slug, rising head	3.10×10^{-4}
	Solid slug, falling head	2.52×10^{-4}
	Solid slug, rising head	3.09×10^{-4}
	Grainsize distribution data	7.85×10^{-7}
PWP	Constant rate pumping test	7.15×10^{-4}

5.2 Evaluation of Constant Rate Pumping Test Data

The hydraulic conductivity estimated for the geological materials at the site was intended to be used to estimate construction excavation inflow rates. Considering this application and the anticipated dewatering conditions, the hydraulic conductivity of these materials would be expected to be best estimated from a test that had reached a steady-state condition. It should be noted, however, that in many cases it is not practical to undertake testing in which a steady-state condition is established due to budget, schedule, available resources, and permitting constraints. It is common to instead carryout relatively short-duration, SWRTs instead.

The constant rate pumping test conducted at the site presented an opportunity to stress the aquifer significantly more than can be achieved relative to typical SWRTs. Nevertheless, the five-hour duration of the test is still generally considered short, and it was not expected that a steady-state condition would be reached. Drawdown versus time plots were created to evaluate whether a steady-state condition had been attained (or nearly reached). A true steady-state condition, barring depletion of the aquifer, would be expected to result in no incremental change in drawdown over time.

The time-drawdown data for MWP 1 through MWP 4 are presented in Figure 2. The incremental percentage change in drawdown between the water level measurements obtained at 240 minutes and 300 minutes into the test (i.e., the final hour of the test) was 2.1%, 4.4%, 6.5%, and 8.3% for MWP 1 through MWP 4, respectively. The incremental percentage change in drawdown over time would be expected to decrease with increasing time and increasing distance relative to the pumping well. This relation was generally confirmed via the pumping test data.

Based on the small observed incremental changes in drawdown, the constant rate pumping test was judged to be adequately close to a steady-state condition to be used as a "best estimate" for hydraulic conductivity at the site.

5.3 Comparison of SWRT Results

The mean and standard deviation of the hydraulic conductivities estimated for each of the different test methods completed for this study were calculated and compared. These mean values and standard deviations are summarized in Table 5.

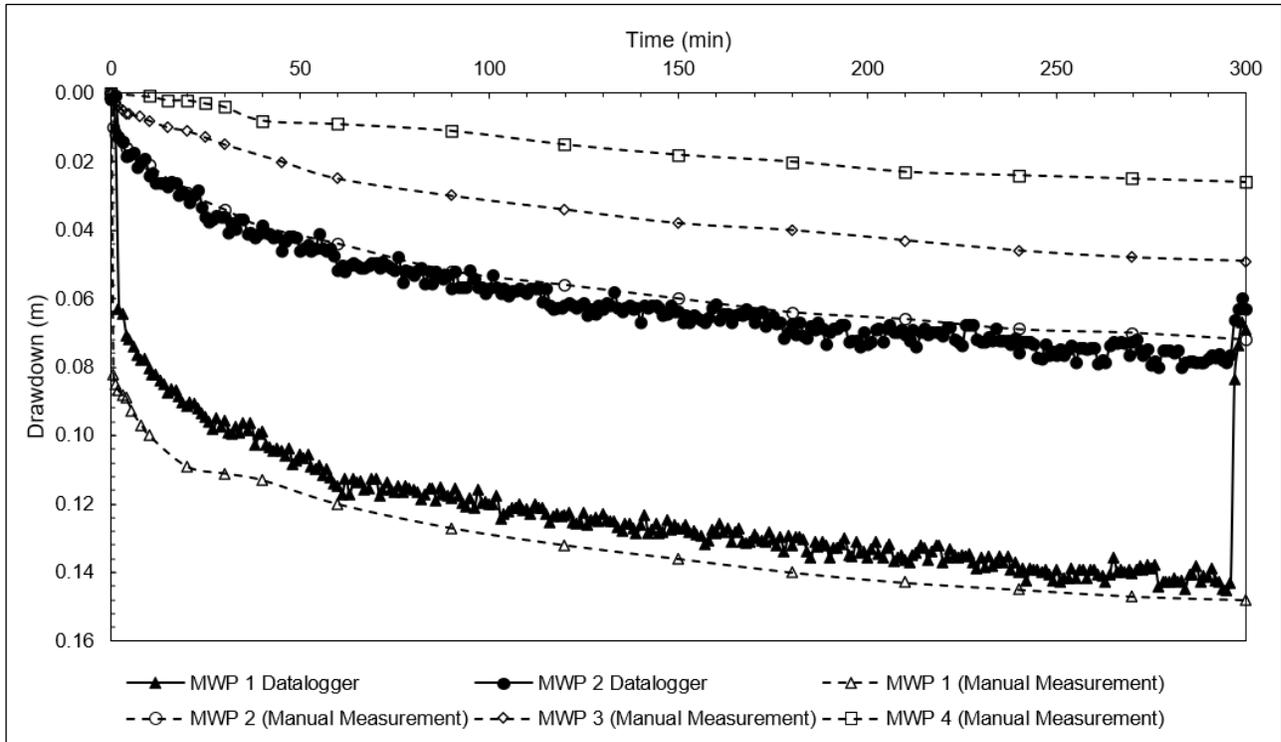


Figure 2. Time-drawdown data from four monitoring wellpoints during 5-hour constant rate pumping test

Table 5. Mean values and standard deviations for estimated hydraulic conductivities

Method	N	Mean (m/s)	σ (m/s)
Solid slug, falling head	7	2.40×10^{-4}	4.5×10^{-5}
Solid slug, rising head	7	2.65×10^{-4}	7.3×10^{-5}
Hydraulic slug, falling head	6	1.80×10^{-4}	7.6×10^{-5}
Short duration recovery test, rising head	1	2.42×10^{-4}	NA
All falling head	13	2.13×10^{-4}	6.8×10^{-5}
All rising head	8	2.62×10^{-4}	6.9×10^{-5}
Grainsize distribution data	5	1.03×10^{-4}	6.2×10^{-5}
Constant rate pumping test	1	7.15×10^{-4}	NA

A few basic observations can be made from the above statistics. First, the average hydraulic conductivity estimated from the rising head tests was approximately one standard deviation greater than the falling head tests. This appears to be primarily due to the hydraulic slug test data, which on average yielded the lowest estimated values out of all SWRT methods conducted for this study. Second, the solid slug (falling head and rising head) and the short duration recovery test produced very similar hydraulic conductivity estimates. Last, the constant rate pumping test data yielded an estimate approximately 3.1 times greater than the hydraulic conductivity values estimated using the SWRT data.

These first two observations were examined further by running two-sample t-Tests (assuming unequal variances)

for the hydraulic conductivities estimated from the different field test methods with multiple paired data. The t-Test results (p-values for the two-sample t-Test) are shown in Table 6. The results generally indicate that a significant difference (at $\alpha = 0.05$) exists between the means of the hydraulic conductivity values estimated using grainsize distribution data and using solid slug tests (both, falling head and rising head). However, the in-situ test methods with multiple data did not produce hydraulic conductivity estimates that differed significantly, nor did estimates using data from falling head tests differ significantly from those using data from rising head tests (not shown in Table 6).

Table 6. Two-sample t-Test results (p-values) for estimated hydraulic conductivity from different test methods

Method	Hydraulic slug, falling head	Solid slug, falling head	Solid slug, rising head	Grainsize distribution data
Hydraulic slug, falling head	NA	0.16	0.09	0.16
Solid slug, falling head	0.16	NA	0.50	<u>0.02</u>
Solid slug, rising head	0.09	0.50	NA	<u>0.01</u>
Grainsize distribution data	0.16	<u>0.02</u>	<u>0.01</u>	NA

Notes: Underlined values display a significant difference in mean values at $\alpha = 0.05$.

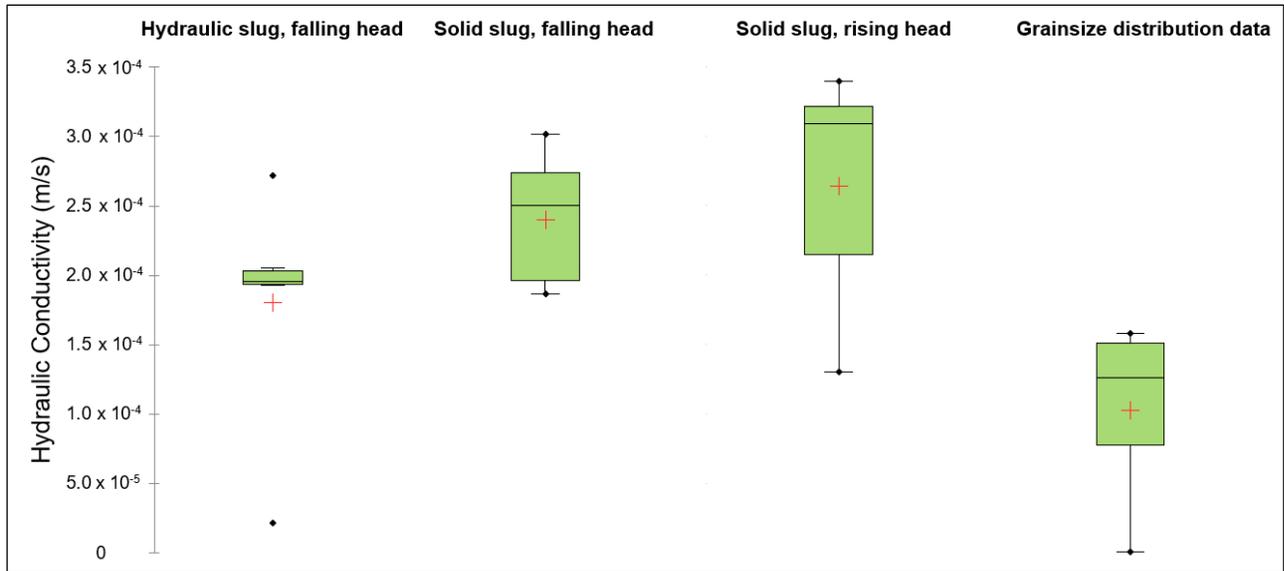


Figure 3. Box plots for hydraulic conductivity estimates from hydraulic slugs, solid slugs, and grainsize distribution data

This same finding that the in-situ test methods did not produce significantly different estimates of hydraulic conductivity can be observed graphically in Figure 3, which presents box plots for each of these datasets. The box plots show minimal overlap between the data distributions corresponding to the solid slug tests and the grainsize distribution data. The box plots also show that solid slug, falling head tests generally produced the narrowest distribution amongst the test methods that were considered at the site. The hydraulic slug method, however, produced estimates with the lowest interquartile range and had a comparable distribution to the solid slug, falling head tests if the hydraulic slug test in MW22-02B is rejected as an outlier.

6 CONCLUDING REMARKS

A reliable estimate of hydraulic conductivity is critically important for many geological and engineering applications. This study compared the estimated hydraulic conductivity from several different common SWRT methods, grainsize distribution data, and a constant rate pumping test to investigate the pros and cons of each field test method considering different end-uses.

Several differences were observed in the statistical parameters calculated from the test results for this study. First, the estimated hydraulic conductivity was on average greater by approximately one standard deviation for rising head tests than for falling head tests. Second, of the field test methods that were conducted, hydraulic slug tests yielded the lowest estimates of hydraulic conductivity. However, the t-Test results did not indicate there was a significant difference (at $\alpha = 0.05$) between the means of the falling head and rising head test datasets, and between any of the individual in-situ test methods with multiple data that were considered.

The estimates using grainsize distribution data were approximately 2.1 to 2.6 times lower than estimates from falling head and rising head test methods, respectively. The t-Test results confirmed there is a significant difference between the means of the hydraulic conductivity estimated using grainsize distribution data versus the in-situ test methods.

Further to the observed statistical differences, the hydraulic conductivity estimated from the constant rate pumping test data was approximately 3.1 times greater than the average estimated hydraulic conductivity for the SWRT data. Intuitively, a test method that is most like the actual conditions under which construction dewatering and contaminant migration are anticipated to take place would be expected to yield a more reliable estimate of hydraulic conductivity for the stated application. For construction dewatering taking place over an extended period, hydraulic conductivity should therefore, ideally, be estimated from a test that has reached a steady-state condition. Rising head test methods were also expected to be preferred over alternative methods, as these would be more similar to the condition of groundwater flowing into an excavation than falling head test methods. The rising head tests conducted for this study resulted in higher estimates of hydraulic conductivity than the falling head tests; however, no significant difference was identified.

For construction dewatering applications, the implications of these observations are that the necessary dewatering rates and the resulting radius of influence could differ by a factor of 2 to 3, or more, depending on the test method used to estimate hydraulic conductivity. The application of a factor of safety is typical for accounting for heterogeneity and other uncertainties inherent to geological media. Applying an increased factor of safety to the hydraulic conductivity value in design calculations may be justified where only SWRT or grainsize distribution data is available. If available, practitioners should give

preference to hydraulic conductivity estimates produced using large-scale pumping tests, followed by SWRT methods, then grainsize distribution data.

7 REFERENCES

- Bouwer, H. and Rice, R.C. 1976. A slug test method for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells, *Water Resources Research*, 12(3): 423-428.
- Devlin, J.F. 2015. HydrogeoSieveXL: an Excel-based tool to estimate hydraulic conductivity from grain size analysis, *Hydrogeological Journal*, Springer, DOI 10.1007/s10040-015-1255-0.
- Freeze, R.A. and Cherry, J.A. 1979. *Groundwater*, Prentice-Hall, Englewood Cliffs, NJ, USA.
- Theis, C.V. 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage, *Am. Geophys. Union Trans.*, 16: 519-524.