48th Cdn Geot. Conf.
Vancouver BC
Sept 1995

IN-SITU MEASUREMENT OF HYDRAULIC CONDUCTIVITY IN SANDS

R.G. Campanella[1], S. Martens[1,2] S. Tomlinson[1,3] and M.P. Davies[1,4]
[1]In-Situ Testing Group, University of British Columbia
[2]Klohn-Crippen Consultants Ltd, Calgary, Alberta
[3]British Columbia Ministry of Transportation and Highways
[4]Klohn-Crippen Consultants Ltd., Richmond, British Columbia

ABSTRACT

By extending the use of the piezocone pore pressure dissipation technology and modifying the commercially available BAT water sampling system, in-situ estimates of hydraulic conductivity in sands can be improved. Beyond unreliable empirical methods based upon estimates of bulk grain-size, large-scale field tests have been the only method available for estimating the hydraulic conductivity in sands. Sand materials represent a large proportion of aquifer materials where water supply, contamination concerns and/or drainage issues require resolution. Recent advances in peizocone and BAT technology present needed alternatives to allow accurate estimates of hydraulic conductivity to be made in these materials.

RÉSUMÉ

A canse de l'extension de là technologie associée avec la dissipaton der pression des pores mesurée par la piezocone, et les modifications de la systéme BAT (utilisée pour la collection de l'ean dans la tevre), les estimes "in-situ" de la conductivité hydrauliqve dans des sables pourrais améliorée. Sauf quil y a des methods empirique qui utilisent la taille des grains, des épreuves à grandes écales avaient être la seul façon d'aquirer une estime de la conductivité hydraulique des sables. Le sol sableux, qui comprise une grande partie d'une aquifére, implique des problémes potentiels concernant la provision de l'eau, la contamination et/où le desséchement. Des avancées récents au milieu de la technologie appartenant la piezocome et la systéme BAT se representent/des alternatives util pour des estimes précis d'être fait pour la conductivité hydraulique dans ces matiè hydraulique dans ces matières.

INTRODUCTION

The in-situ measurement of hydraulic conductivity in sands traditionally requires a large scale field pumping test with several observation wells. The use of falling or rising head tests in screened wells can also be successful but the data is limited to the screened interval and often the well installation impacts the measured result considerably. Either method is expensive and provides single point data. As it is within sands and gravels that most water supply and contamination transport concerns exist, accurately assessing the in-situ value of hydraulic conductivity is of large practical importance.

This paper presents recent advances with the piezocone and BAT which allow measurements of in-situ hydraulic conductivity into the medium sand range.

Piezocone Estimates of Hydraulic Conductivity

The piezocone is well-established as a useful means for calculating the coefficient of consolidation, and thus hydraulic conductivity, in fine-grained materials (Robertson et al, 1992). The cone displaces pore water as it penetrates the soil, creating pore pressures in excess of hydrostatic. This excess pressure may be positive or negative. With cessation of pushing, this excess pore pressure decays to equilibrium; how rapidly this occurs is a function of the soil's hydraulic conductivity. In low hydraulic conductivity soils the decay is very gradual and easily monitored, but coarser-grained soils drain very quickly. Recently modified piezocone data acquisition techniques have been developed to monitor very rapid pore pressure dissipations.

Hydraulic conductivity can be determined from:

$$K = c \cdot m \cdot \gamma_w \quad [1]$$

where:
c = coefficient of consolidation
m = compressibility
γ_w = unit weight of water

The coefficient of consolidation is proportional to the time factor by:

$$c = \frac{T_x \cdot r^2}{t_{50}} \quad [2]$$

where:
T_x = time factor at time x
r = radius of the probe
t_x = time for x percent dissipation

These equations allow plots of time factors versus decay of excess pore pressure (U, which is proportional to the degree of consolidation) to be made (Figure 1). For low conductivity soils, several different relationships have been proposed based upon cavity expansion solutions (Gillespie, 1981). Pore pressure records measured over time are used to determine t_{50}, and c and thus K are calculated using the above equations.

For higher conductivity soils, no equivalent U-T curves currently exist in literature. The curves presented in this paper are, to our knowledge, the first for sand soils.

Calibration of Piezocone Time-Factor Curves

To determine T factors for the piezocone, curves were generated by using the hydraulic conductivities measured by the KBAT to calculate c. In this series of experiments, two curves were generated from fast dissipation records at different depths from one hole; a third curve was made for comparison using traditional slow dissipation results from a clay in a nearby hole. The parameters used for the curves are listed in Table 1 while the curves themselves are shown in Figure 1. It can be seen that t_{50} is inversely proportional to hydraulic conductivity, which is intuitive.

TABLE 1 Soil Parameters From Kidd II Research Site

Hole	Depth (m)	Soil type	Compressibility (m^2/kN)	Hydraulic Conductivity (m/s)	t_{50} (s)
KD15	10.82	sand	1.33×10^{-3}	9×10^{-7}	0.51
KD15	12.85	sand	1.24×10^{-3}	2×10^{-7}	2.31
KD02	31.20	clay	1.93×10^{-4}	4.1×10^{-10}	315.71

Having established a U-T plot for sands, hydraulic conductivities can now be calculated by simply recording pore pressure dissipations. These curves should be valid for materials of similar compressibility. The examples given are preliminary results meant only to show the potential of this technique as they are dependent on accurate permeabilities from the KBAT.

To practically achieve meaningful rapid dissipations in what are usually described as "drained" soils, two important aspects are required:

1. an accurate and sensitive pore pressure transducer capable of ± 0.01 m resolution; and

2. data acquisition during dissipation mode at least as fast as 0.02 sec per reading for the first few seconds.

The recent advances in the piezocones and data acquisition software/hardware used at UBC allow these minimum standards to be met. Adapting commercial cones and systems to these standards would require minimal effort.

The UBC Modified KBAT System

The UBC KBAT system is an in-situ tool which provides an efficient and cost-effective means of determining in-situ hydraulic conductivity of all materials from clays through to fine sands. The UBC KBAT system is a modified form of the BAT hydraulic conductivity device, as described by Torstensson (1984). In the UBC KBAT, 3/8 inch Swagelok valves replace the needle and septum system to allow for much higher rates of flow (Figure 2). This effectively allows measurement of hydraulic conductivities almost two orders of magnitude higher than was previously attainable using the original system.

The KBAT test procedure typically follows a piezocone test with pore pressure dissipations. The piezocone results provide stratigraphic information and identify regions where KBAT data is desired. The KBAT test can also be run independent of the piezocone. The KBAT has a 50 mm diameter tip, which allows it to follow a 36 mm diameter piezocone sounding hole while ensuring good contact with the perimeter of the hole. The KBAT filter tip can be pushed down a piezocone hole quickly, and the collection cylinder in the wire-line KBAT porewater sampler probe is easily evacuated with a vacuum pump. Once the filter is at the desired depth, the KBAT probe is lowered down the casing until the Swagelok valve on the probe connects with the valve on the end of the filter tip. This dual valve system ensures the sample integrity, since fluid cannot flow into the cylinder until both valves have been opened. Fluid then flows into the cylinder as a result of the pressure difference between the KBAT cylinder and the water in the surrounding formation. The first test at each depth purges the filter and the cylinder. The test is then repeated, the pressure data is recorded at appropriate time intervals by means of a pressure transducer at the upper end of the collection cylinder, and the sample from the cylinder is collected. The volume of the sample is measured to compare against the known volume of the cylinder as a check of the procedure. The fluid collected can also be used for in-situ geochemical evaluations. The final measured pressure, corrected for the distance between the transducer and the filter tip, should also agree with the static pore pressure measurements using the piezocone at that depth.

During the test, the progress can be monitored continuously by calculating the volume of water which has entered the cylinder, based on the pressure recorded by the pressure transducer in the KBAT probe. This calculation can be done in real time by the data acquisition system and is very useful, as it allows the operator to determine when the test is complete and the probe can be withdrawn.

A check of the theory used to determine the hydraulic conductivity using the KBAT can be carried out. The theory is based on the work of Hvorslev (1951), who stated the flow equation:

$$q = F \cdot K \cdot (u_o - p_t) \qquad [3]$$

where:
q = fluid flow (m^3/s)
F = flow factor (m)
K = hydraulic conductivity (m/s)
u_o = static pore pressure at the filter depth (m H_2O)
p_t = pressure at any time inside the KBAT cylinder (m H_2O)

This is simply a restatement of Darcy's empirical law, with the ratio of the area to the length of the flow path combined into the flow factor:

[4] $$F = \frac{A}{L}$$

The head driving flow into the KBAT cylinder is thus the difference between the head outside the drawdown cone surrounding the probe and the pressure inside the cylinder. Since the internal pressure changes with time as water flows into the cylinder, the rate of flow also changes with time.

The use of a constant flow factor is possible since for a given filter geometry this ratio remains constant during the test. For a cylindrical filter with the ratio of length to diameter greater than two, the flow factor can be approximated by the following equation given by Hvorslev (1951), cited in Petsonk (1984):

[5] $$F = \frac{2 \cdot \pi \cdot L}{\ln\left[\frac{L}{d} + \sqrt{1 + \left(\frac{L}{d}\right)^2}\right]}$$

where:
L = filter length (m)
d = filter diameter (m)

In the case of the UBC filter tip where the filter length is equal to the diameter, the filter geometry does not quite satisfy the simplifying assumptions used to derive the above formula. The flow factor was taken from the chart reproduced in Figure 3 by Tavenas et al. (1986). Al-Dhahir and Morgenstern (1969) confirmed the validity of Hvorslev's flow factor with numerical simulations.

The flow factor assumes an isotropic porous medium (K_h=K_v), which is practically never true in naturally deposited sediments. However, the derivation of the flow factor assumes that the majority of the flow is horizontal towards the filter, and for natural sediments with K_h>K_v, this would certainly be the case. Regardless, any error in the flow factor would be small, as the flow factor only varies by a factor of about three for practical filter geometries. This is easily within the range of confidence for estimating hydraulic conductivities.

Boyle's ideal gas law is the other fundamental principle used to derive an expression for the hydraulic conductivity based on the KBAT test. This relates the volume of air inside the collection cylinder to the pressure change as measured by the pressure transducer. The resulting formula was developed by Bengtsson and is presented in Petsonk (1984):

[6] $$K = \frac{p_0 \cdot V_0}{F \cdot t} \cdot \left[\frac{1}{u_0 \cdot p_0} - \frac{1}{u_0 \cdot p_t} + \frac{1}{u_0^2} \cdot \ln\left(\frac{p_t}{p_0} \cdot \frac{p_0 - u_0}{p_t - u_0}\right)\right]$$

where:
p_o = pressure at the data point previous to the time of interest (m H_2O)
t = time increment between two consecutive data points (s)
p_t = pressure at the time of interest (m H_2O)

This formula does not take into account the pressure head due to the column of water inside the KBAT probe, which changes during the test. During testing, however, this effect was found to be negligible for pressure differences between the KBAT cylinder and the surrounding pore water greater than 5 metres of water. Several other formulae were found in the literature and also evaluated. Formula [6] given above was found to yield the most reasonable results and be the easiest to use. This formula been applied by others between the pressure at the beginning of the test and the pressure at any time, which has the effect of calculating the secant slope of the pressure - time curve. The method recommended here is to apply the formula between two consecutive data points, which has the effect of calculating the tangent slope. The results of the Bengtsson (1984) formula and the formula recommended by BAT Envitech (1987) are shown in Figure 4.

A series of falling head permeability tests were performed in an attempt to correlate these results with the hydraulic conductivity determined by the KBAT. Due to segregation of the fines in the silty sands sampled from the Kidd II site in Richmond, it was not possible to obtain reliable results from the falling head tests on these sands. This is a result of the inherent problem of trying to recreate the insitu conditions in the laboratory. A series of uniform sands were then tested with the falling head test and the KBAT in the laboratory, but the hydraulic conductivities of these sands were too high to be measured even by the UBC modified KBAT system. Lab tests that were performed showed that the limitation to the flow was in the valves, and the presence of a clean filter does not affect the results. In field conditions, clogging of the filter from fine sediments may be a concern, but this can be checked by comparing tests in a bucket of clean water before and after the field tests are performed.

The pressure - time data was run through a low pass filter using signal processing software to remove the noise in the signal. The formula used to calculate the hydraulic conductivity is sensitive to noise in the input data, and since the hydraulic conductivity is calculated as a function of time, noisy data produces noisy results. The calculations for determining the hydraulic conductivity are easily performed on a spreadsheet. The results from a KBAT hydraulic conductivity test at the Kidd II site in Richmond are shown in Figures 4, 5, and 6. As shown, it is important to plot the pressure and water volume in the cylinder as well as hydraulic conductivity against time, as these plots provide insights into the meaning and integrity of the data. Figure 6 shows that for a test in which the hydraulic conductivity of the soil is within the range of the UBC KBAT probe, the volume versus time curve has three distinct segments. The first segment, with a steep slope, is interpreted as measuring the maximum flow the valve system is capable of passing. The next segment is the measurement of the hydraulic conductivity of the soil, and the level segment of the curve occurs when the main cylinder has filled and remaining pressure is the cylinder is equalizing. Therefore, the region of interest for the data from this test is between 10 and 35 seconds. The hydraulic conductivity of the soil is interpreted as 2.5×10^{-7} m/s.

The KBAT system based on the needle and septum has a limiting hydraulic conductivity of about $1x10^{-6}$ m/s (BAT Envitech 1987). The Swagelok system developed at UBC has expanded this range to an upper value of about $5x10^{-5}$ m/s. A further attempt to expand the range by switching to a higher flow capacity Swagelok valve had little effect on the range of hydraulic conductivity values that are measurable, and demonstrated the limitations of the system. It is felt that the upper limit of hydraulic conductivity measurable with this type of system has been reached.

A means of measuring the air temperature inside the cylinder could be added to improve the accuracy of the pressure measurements, but the effect of temperature on the results is small.

One disadvantage of the UBC modified KBAT system is that it does not have the advantage of taking a sealed, guaranteed unmixed sample, as with the original BAT hypodermic needle method. When extremely rigid requirements on the purity of the sample are not in force, as in screening applications, the UBC KBAT is a quick and easy compliment to the water sampling process.

The use of the KBAT system in sands is relatively new, and there are opportunities for further research. More research is necessary in validating the flow factors for filters with a length to diameter ratio of less than one. This research should take the form of empirical test results and numerical modelling. The remoulding effects due to the installation of the filter tip in the soil has been shown to affect the measured conductivity in lower conductivity materials (Tavenas et al. 1986). These effects should also be investigated for sands. One further issue of a practical nature that should be investigated is that to date, tests have only been performed with the UBC modified KBAT at depths less than 25 metres below the groundwater table. The high water pressure against the lower Swagelok valve at greater depths may make it difficult for the valves to open under the weight of the KBAT probe.

SUMMARY

This paper has presented two new complimentary methods for estimating in-situ hydraulic conductivities using existing but modified in-situ tools. The modified KBAT and the rapid piezocone dissipation text allow measurements of hydraulic conductivity into at least the fine sand range. Although fine sands may be the practical limit for the KBAT, the rapid dissipation from piezocone method can potentially be used in coarser materials given adequate transducer and data acquisition capabilities.

REFERENCES

AL-DHAHIR, Z.A. AND N.R. MORGENSTERN, 1969. "Intake Factors for Cylindrical Piezometer Tips", Soil Science, Vol. 107, No. 1, pp. 17-21.

BAT ENVITECH. 1987. “Derivation of Formulas for BAT Permeability Calculations.”

GILLESPIE, D.G., 1981. The Piezometer Cone Penetration Test. Unpublished Masters Thesis, University of British Columbia.

HVORSLEV H.J. 1951. “Time Lag and Soil Permeability in Ground Water Observations.” U.S. Corps of Army Engineers, Waterways Experiment Station, Vicksburg, Miss., Bull. 36. 50pp.

PETSONK, A. M. 1984. “The BAT Method for In Situ Measurement of Hydraulic Conductivity in Saturated Soils.” Undergraduate Thesis in Hydrogeology, University of Uppsala, Sweden. 54pp.

ROBERTSON, P.K., SULLY, J.P., WOELLER, D.J., LUNNE, T., POWELL, J.J.M., AND GILLESPIE, D.G., 1992. Estimating coefficient of consolidation from piezocone tests. Canadian Geotechnical Journal, Vol 29, pp 539-550.

TAVENAS F. AND TREMBLAY M., LAROUCHE, G. AND LEROUEIL S., 1986. “In-Situ Measurement of Permeability in Soft Clays”, Proceedings of In-Situ ‘86, Geotechnical Division, ASCE, Blacksburg, VA.

TORSTENSSON, B.A., 1984. “A New System for Ground Water Monitoring”, Ground Water Monitoring Review. V.4 (4), pp131-138.

FIGURES

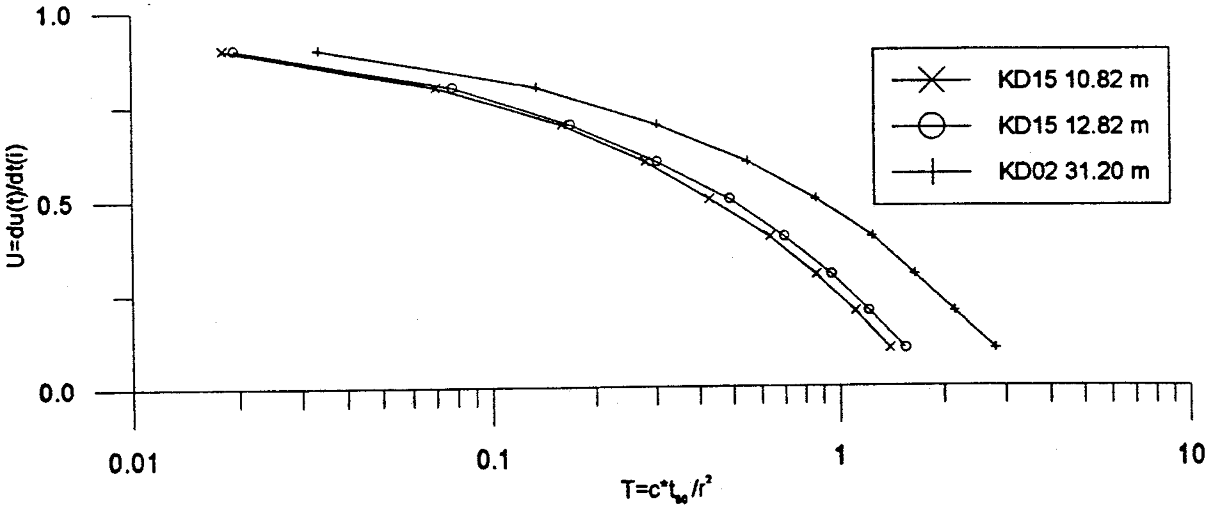

FIGURE 1: Time Factor Curves for Piezocone Dissipations in Sands

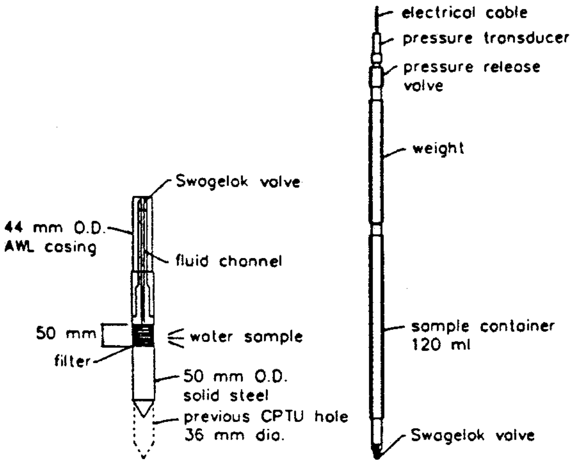

FIGURE 2: UBC Modified BAT Hydraulic Conductivity Device

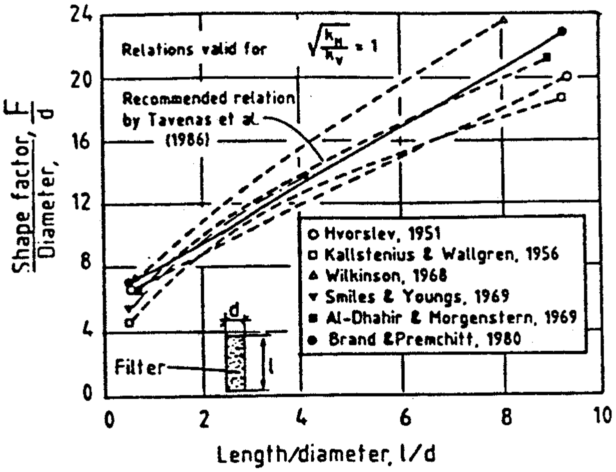

FIGURE 3: Shape Factor for In Situ Measurement of Hydraulic Condictivity in Cylindrical Piezometers (Tavenas et al.1986).

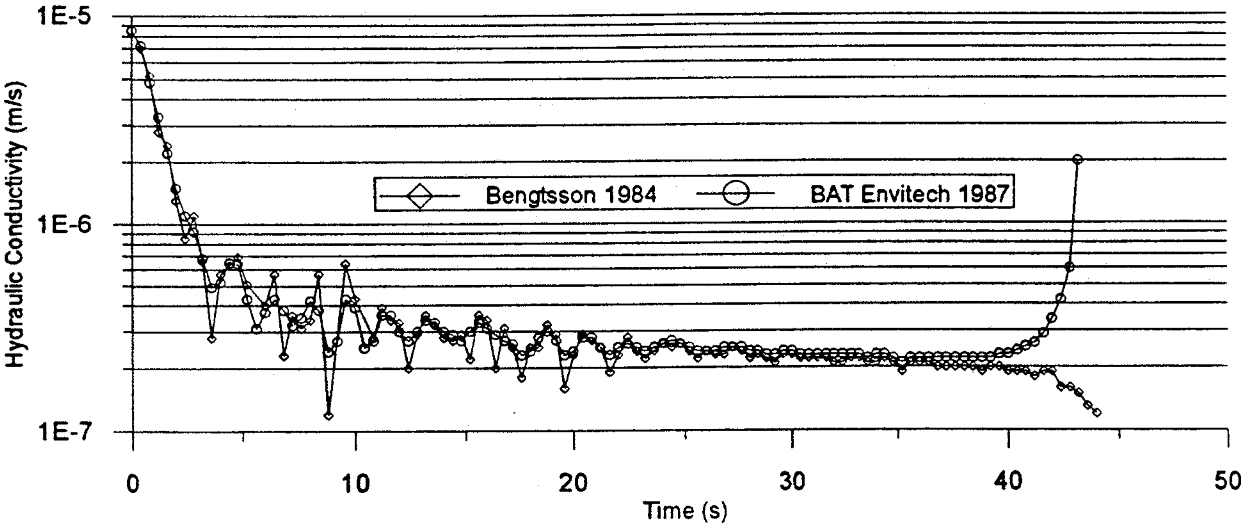

FIGURE 4: KBAT Test Results - Kidd II site, 8.6 metres depth

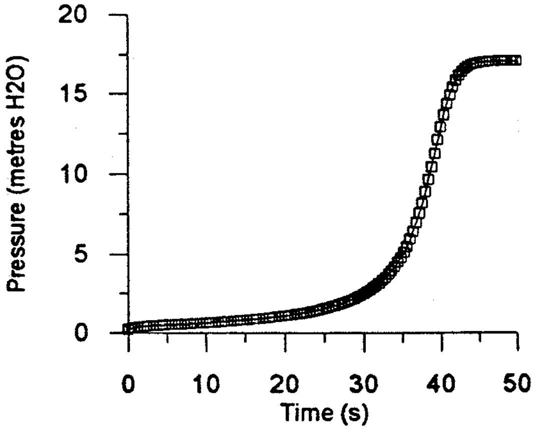

FIGURE 5: KBAT Test Results - Kidd II, 8.6 metres

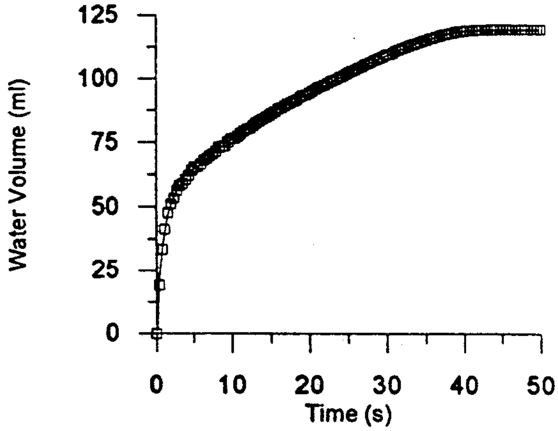

FIGURE 6: KBAT Test Results - Kidd II, 8.6 metres