A Rapid In-Situ Hydraulic Conductivity Measurement in Sands using a UBC Modified BAT Penetrometer

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ABSTRACT

Hydraulic conductivity measurements for hydrogeological site characterization are traditionally done by expensive, time consuming and labor intensive large scale pump tests and single well testing. The UBC modified KBAT penetration system offers an alternative method for performing in-situ tests. Based on the Hvorslev method of evaluation, the KBAT outflow test is capable of measuring the hydraulic conductivity of sands up to a limit of 1×10^{-4} m/s. Major advantages of the KBAT outflow test includes elimination of filter clogging, limiting fines migration and minimizing any changes in effective stress by maintaining a low gradient. The test is fast, easy to perform and measures K at a specific depth. When used in conjunction with piezocone measurements, the result provides effective and cost efficient hydrogeological site characterization.

RÉSUMÉ

Les mesures de conductivité hydraulique pour la caractérisation d'un site hydrogéologique sont traditionnellement faites par des tests de pompage à grande échelle et le sondage d'un seul puit ce qui est coûteux et qui demande beaucoup de temps ainsi qu'un travail intensif. Le systéme de pénétration KBAT modifié de l'Université de Colombie-Britanique offre une méthode alternative d'éxécution de tests in-situ. Basé sur la méthode Hvorslev d'évaluation, le test d'écoulement KBAT est capable de mesurer la conductivité hydraulique des sables jusqu'à une limite de 1×10^{-4} m/s. Les avantages majeurs du test d'écoulement KBAT comprennent l'élimination de l'encrassement du filtre, la limitation de la migration des fines et la réduction au minimum de tout changement des contraintes effectives par le maintien d'un faible gradient. Le test est rapide, facile d'éxécution et mesure K à une profondeur spécifique. Lorsque utilisé conjointement avec des mesures de piézocone, le résultat fournit une caractérisation de site hydrogéologique efficace et économique.

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INTRODUCTION

Hydraulic conductivity is one of the most important parameters in hydrogeological site characterization. Hydraulic conductivity measured in-situ is traditionally done by evaluating large scale pumping tests or smaller scale single well slug tests. To do these types of tests, screened wells and piezometers must be installed at considerable expense, and data is often only single point data. A unique penetrometer water sampling probe was developed by Torstensson (1984) called a BAT probe. A porous tip, sealed with a flexible disk (septum) is pushed with casing to a particular depth. A wire-line sample chamber is lowered down the casing and makes contact with the porous tip with the use of a double-ended hypodermic needle (type used in blood sampling) which simultaneously punctures the flexible disk on the tip and the flexible disk sealing the evacuated sample chamber. A series of wire-line weights are used to provide the needle insertion force. When the sampler is pulled up, the hypodermic needles simultaneously pull out of the flexible disks, thus sealing off both the porous tip and sample chamber. The first sample is used to purge the system and subsequent samples are used for analyses. This unique, yet simple, apparatus provides a reliable hermetically sealed system which maintains the integrity of both sampled fluids and vapors and has been evaluated by the EPA (Blegen et al. 1988). Torstensson's design also accommodated a pressure transducer to record the pressure in the sample chamber which allows one to calculate change in volume with time and therefore to calculate hydraulic conductivity, K. The hypodermic needles limited the K measurements to a maximum value of about $1\text{x}10^{-6}$ m/s (Petsonk 1985) and was particularly good for silts and clays. If the sample chamber had pressurized fluid one could perform an outflow test to measure K and to inject a fluid into the soil water. If the wireline were lowered with only the pressure transducer and hypodermic needle, but without the sample chamber, the system measured equilibrium water pressure at the porous tip. Because of the small volume of water in the tip and the very small needle volume, the piezometeric levels came to equilibrium very rapidly (less than 15 minutes) even in clays.

Campanella et al. (1995) modified the BAT probe by redesigning the tip and replacing the hypodermic needles with Swagelok quick connect valved fittings which could mate, seal and open with the application of a weighted sample receptacle. The use of the spring-loaded quick connect valves eliminated the clogging, bending and restricted flow of the hypodermic needles yet maintains sample integrity to a large extent.

The modified KBAT system and outflow procedure introduced in this paper is capable of measuring hydraulic conductivities of up to $1\text{x}10^{-4}$ m/s. The outflow procedure also eliminates the difficulty of filter clogging, and allows the operator the flexibility of controlling the fluid gradient and therefore limiting the migration of fines and changes in effective stress.

THE MODIFIED OUTFLOW KBAT SYSTEM

In the UBC modified KBAT, 3/8 inch Swagelok valves replace the needle and septum system used by Torstensson (1984) to allow for much higher rates of flow. The lower part of the KBAT system consists of a 50mm diameter probe that can easily be pushed down the 44mm diameter

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hole left by a piezocone to ensure good soil contact. Alternately, it can be pushed independently. The probe has a 60° conical tip, a middle filter section, and an upper section connected to 44mm O.D. AWL flush joint casing. In the middle of the upper connection, a pin-ended Swagelok valve is connected to a conduit which runs through the probe to the filter section. The second part of the KBAT system consists of the wireline portion made up of a stainless steel sample chamber at the bottom by a box-ended Swagelok valve, attached to a set of weights with a through conduit which is sealed at the top by a pressure transducer. The sample chamber can be pressurized up to 700kPa (~70mH$_2$O). This section is lowered inside the casing by a reinforced electrical cable that allows continuous pressure readout at surface. Flow out of the KBAT tip through the filter cannot occur until the two Swagelok valves are joined. Various setups of the KBAT probe are used, but a typical probe configuration is presented in Figure 1.

The procedure for the KBAT inflow test, or pore water sample, is to evacuate the KBAT sample chamber to a pressure equivalent to -10 mH$_2$O. When the wireline section is connected to the probe, water flows into the sample chamber. For the outflow test, a measured volume of water is added to the sample chamber and pressure is applied. When the wireline section is connected to the probe, water flows from the sample chamber to the formation. This allows the operator the flexibility to easily and accurately control the maximum pressure difference between the KBAT and the formation. The significance of this will be discussed with the results. As the pressures between the KBAT and formation equalize, the pressure and time data are recorded at surface. The data is run through a low pass filter using signal processing software to remove any noise in the signal. The data is entered into an EXCEL spreadsheet template developed for the hydraulic conductivity theory. Other input data such as static water level, type of probe, filter length, filter diameter and KBAT chamber and water volume are also entered into the spreadsheet. Plots of K, pressure, and fluid volume are plotted against time. An example spread sheet is presented in Figure 2. Plots of K, pressure, and fluid volume vs. time are presented in Figures 3 and 4.

HYDRAULIC CONDUCTIVITY EVALUATION THEORY

Using the ideal gas law at constant temperature to obtain volume change from gas pressure change, and Hvorslev's (1951) method for evaluating a single well test in an unconfined aquifer, the following equation can be derived:

$$K = \frac{P_o \cdot V_o}{F \cdot (t_3 - t_1)} \cdot \frac{1}{a} \cdot \left(\frac{1}{P_1} - \frac{1}{P_3} + \frac{b}{a} \cdot \ln\left[\frac{P_1}{P_3} \cdot \frac{(a + b \cdot P_3)}{(a + b \cdot P_1)} \right] \right) \qquad [1]$$

where a = $\left[H + \frac{P_{atm}}{\gamma_w} - h' \right]$(m), b = $\left[\frac{-1}{\gamma_w} \right]$ (1/kgm/m^{3}s^2), $F = \frac{2 \cdot \pi \cdot L}{\ln\left(\frac{L}{D} + \sqrt{1 + \left(\frac{L}{D} \right)^2} \right)}$, P$_o$ is initial absolute air pressure in the KBAT chamber (Pa), V$_o$ is initial volume of air in the KBAT chamber, P$_1$ is absolute KBAT chamber pressure (Pa) at time step 1, t$_1$ is time (seconds) from the start of the test at time step 1, t$_3$ is time (seconds) at time step 3, H is the aquifer static water

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height (m) from mid-filter, P_{atm} is absolute atmospheric pressure (Pa), γ_w is unit weight of water (9.81 KN/m^3), h' is height of water (m) in KBAT chamber from mid-filter, L is length of filter (m), and D is diameter of filter (m).

This represents the solution at time t_2, using the pressures at the previous and following time steps t_1 and t_3 respectively. This approximates the tangent slope of the pressure-time curve at time t_2. Refer to Figure 5 for a schematic illustration comparing piezometer and KBAT systems.

LABORATORY CALIBRATION AND VERIFICATION OF THEORY

A lab testing chamber was constructed to simulate conditions of high permeability soil and static water levels up to 3.7 m above mid-height of the filter zone. The chamber was simply a vertical 4m length of PVC pipe 300mm (12 inches) in diameter, sealed at the bottom and open at the top. The chamber was filled with water and the UBC KBAT probe attached to AWL casing rods was lowered to the bottom. KBAT testing in water alone made it possible to determine the maximum measuring limit of the system and to identify the limits of each component of the system. Comparison of inflow and outflow tests allowed the evaluation of the effect of fluid velocity on the results while eliminating factors such as filter clogging. A special perforated (many 5mm diameter holes) KBAT sample chamber was used to allow water to flow up or down the AWL casing pipe to simulate an open standpipe rising (inflow) or falling (outflow) slug test. The data was evaluated using Hvorslev's method, commonly used in professional practice, and results compared to outflow KBAT evaluations under similar conditions. Agreement of the two tests confirmed the validity of the Hvorslev KBAT outflow equations.

It was determined that evacuating the KBAT chamber created a large pressure gradient and the consequent high velocity caused turbulent flow and resulted in an under estimate of hydraulic conductivity for highly permeable soil. With the commonly used 48mm filter and either 3/8 inch or 1/2 inch Swagelok valves in place, the highest measurable K value of about 1×10^{-4} m/s approaches the limit of the filter alone.

FIELD TESTING

Field tests were performed at 2 sites in Richmond, British Columbia. The KIDD 2 site is located on #4 Road, 300m from the North Arm of the Fraser River. The site is characterized by thin units of clay to sandy silt layers down to a depth of approximately 8m, and a permeable sand layer to approximately 21m. Several piezometers and a pumping well had been installed at the site for the UBC Hydrogeology Field School. The site has been well characterized by the combination of pump tests, single well slug tests, continuous core, and piezocone investigations, with sand aquifer K values ranging from 1×10^{-4} to 7×10^{-4} m/s. The objective of the KBAT testing at the KIDD 2 site was to perform evaluations in a highly permeable sand unit where extensive test were available for validation of KBAT procedures.

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The second field site is located off Highway 99 at the south end of the George Massey Tunnel on Deas Island. Although the location had no installed piezometers, the geologic setting was well defined by previous piezocone soundings as a relatively homogenous, loose silty sand unit from 4m to 21m below ground surface. It was realized that the sand aquifer at the KIDD 2 site was more permeable than the measuring limits of the equipment, so a slightly less permeable soil unit was desired to continue developing the KBAT outflow system. The objectives of the field tests were to improve the outflow test methodology, continued comparison of inflow and outflow tests, and address concerns of fines migration and soil fracturing or vertical flow around the probe due to over pressuring the KBAT.

The field testing of the KBAT probe identified limitations with the inflow test, specifically filter clogging. The close agreement of the inflow test and the rising head test results with the KBAT probe confirmed the validity of the KBAT evaluation. The KBAT outflow test prevents filter clogging due to fines migration, and allows the flexibility of setting the pressure gradient between the formation and KBAT chamber at the appropriate value. The KBAT outflow test also shows excellent repeatability. The disadvantage of performing outflow tests is that a fluid sample cannot be collected on the same probe descent.

SUMMARY

This paper has presented a new method for estimating in-situ hydraulic conductivities in sandy soils using an existing but modified in-situ tool. The modified KBAT probe and outflow test evaluation allows measurements of hydraulic conductivity up to $1x10^{-4}$ m/s. The outflow evaluation based on Hvorslev's method has proven to match open standpipe rising and falling head tests similar to those performed in professional practice. The outflow procedure eliminates the problem of filter clogging, and allows the operator the flexibility to set the maximum pressure gradient. Thus, changes in effective stress and fines migration are limited. The repeatability of the evaluations has proven to be excellent. The outflow test is fast, easy to perform and measures K at a specific depth. The combination of KBAT outflow evaluations and piezocone soundings provides an effective and cost efficient hydrogeological site characterization.

CONCLUSIONS

1. The major modification to the original BAT by Torstensson, 1984, is the replacement of the hypodermic needle with Swagelok Quick Connect locking valves.
2. The recommended probe dimension for use down previous piezocone holes is 50mm diameter with a 50mm long filter and a solid 50mm diameter section that is 200m long above and below the filter. With a 60° conical tip and box-ended AWL square threaded casing joint, the probe is about 600mm long.
3. Laboratory tests with the UBC modified KBAT probe in a water column showed that the usual inflow KBAT test with an evacuated sample chamber caused very high gradients resulting in very high velocity and turbulent flow through the quick connect valves

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(substantiated by average Reynold's number calculations) resulting in an under estimate of hydraulic conductivity. In high flow conditions in high K soils the flow velocity must be controlled.

4. With reduced gradient testing there was very close agreement between inflow and outflow KBAT tests and inflow and outflow standpipe slug tests validating the method of calculating K by the KBAT Eq. 1. The lab tests clearly show that when using the recommended 50mm long by 50mm diameter porous plastic filter (nominal 125 micron size) the highest measurable K value of about 1x10^{-4} m/s is limited by the filter characteristics and is about the same whether the 3/8 inch or 1/2 inch Swagelok valve is used.
5. Field testing performed at the calibrated KIDD 2 site clearly demonstrated the importance of filter plugging due to fines migration during inflow tests where K values can be decreased by as much as 2 orders of magnitude or even more in sands with silty fines. This affect is not a factor in plastic clayey silts and silty clays where the K of the soil is 10^{-7} to 10^{-10} m/s or more than 3 orders of magnitude lower than the filter and fines migration is a minimum.
6. To accurately measure K in sandy soils it is mandatory that only OUTFLOW tests be performed to eliminate filter plugging.
7. Field tests at the Massey site in the fairly uniform loose fine sands show that outflow KBAT tests reliably measure K and agree with outflow (falling head) standpipe slug tests at the same depth.
8. Since the modified KBAT measures K at a specific depth and over only 50mm (2 inches) of depth it is expected to give lower average values of K when compared to a larger scale area that is impacted by a pumping test. The pumping test may be controlled by a few very permeable layers while the KBAT outflow tests may not have even sampled any of those layers. Therefore, it is important to carefully choose the depths of K testing. This can be done by use of the piezocone test to evaluate the detailed stratigraphy, especially where gradational and density changes exist, as in delta deposits. When KBAT tests are done in the hole left by a piezocone test, concern over lateral variability is eliminated.
9. Additional work is needed to develop the KBAT to measure K values approaching 10^{-3} m/s which can be achieved within an even smaller filter of the order of 10mm long or less. L/D ratios less than 0.2 will require field and lab calibration as well as numerical modeling to determine the appropriate F factor for Hvorslev's equation.
10. An obvious disadvantage of outflow tests is that you cannot take pore water samples which requires an inflow test but which would partially clog the filter. Also, outflow KBAT tests will dilute and/or affect the integrity of the pore water and cannot be mixed with water sampling. It is recommend that when both KBAT tests and water samples are required that water sampling be done first on the way down and outflow testing can be done in the same hole after the filter is changed. If time is short it is possible to do outflow tests on the way up after inflow sampling on the way down since results suggest that after two outflow tests the filter is cleared or unplugged and results are essentially the same as virgin outflow tests. These should be checked however before using this approach.

ACKNOWLEDGMENTS

Support for the development of the KBAT was provided by the Natural Sciences and

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Engineering Research Council of Canada (NSERC), the Civil Engineering Department at UBC and technicians Scott Jackson and Harold Schrempp. Thanks are also due to the many research students who helped with the KBAT testing and developmental ideas over the past 3 years, especially Scott Martens, Grant Bonin, Henrick Kristensen and Chris Daniel.

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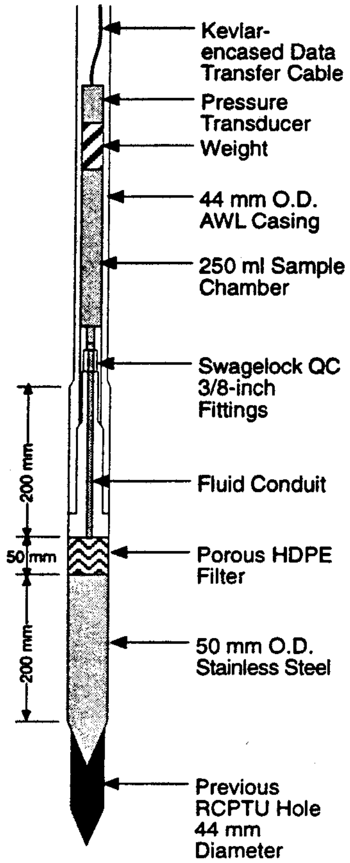
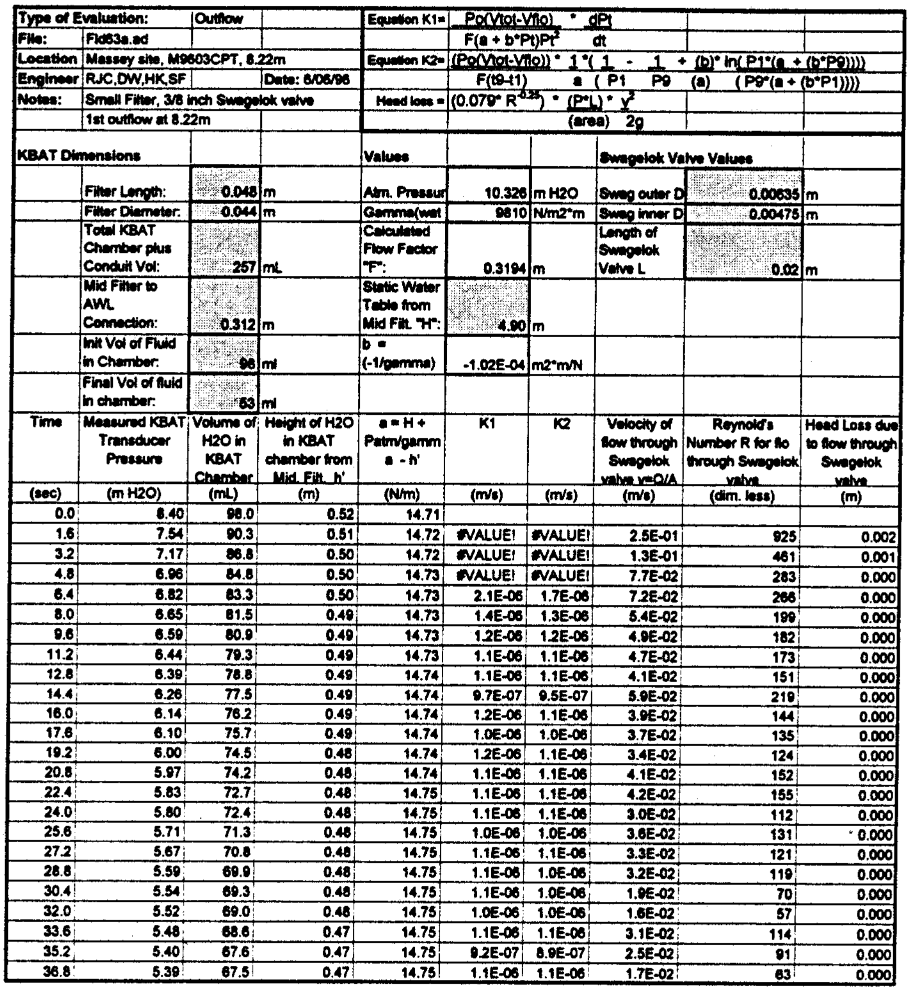


FIGURE 1. Schematic Illustration of KBAT Probe.



Type of Evaluation:		Outflow		Equation K1=	Po(Vtot-Vflo) * dPt				
File:	Fld63a.ad				F(a + b*Pt)Pt² dt				
Location	Massey site, M9603CPT, 8.22m			Equation K2=	(Po(Vtot-Vflo)) * 1 *(1 - 1 + (b)* ln(P1*(a + (b*P9))))				
Engineer	RJC,DW,HK,SF		Date: 6/06/96		F(t9-t1) a (P1 P9 (a) (P9*(a + (b*P1))))				
Notes:	Small Filter, 3/8 inch Swagelok valve			Head loss =	(0.079* R^-0.25) * (P*L) * v²				
	1st outflow at 8.22m				(area) 2g				
KBAT Dimensions				Values			Swagelok Valve Values		
	Filter Length:	0.048	m	Atm. Pressur	10.326	m H2O	Sweg outer D	0.00635	m
	Filter Diameter:	0.044	m	Gamma(wat	9810	N/m2*m	Sweg inner D	0.00475	m
	Total KBAT Chamber plus Conduit Vol:	257	mL	Calculated Flow Factor "F":	0.3194	m	Length of Swagelok Valve L	0.02	m
	Mid Filter to AWL Connection:	0.312	m	Static Water Table from Mid Filt. "H":	4.90	m			
	Init Vol of Fluid in Chamber:	98	ml	b = (-1/gamma)	-1.02E-04	m2*m/N			
	Final Vol of fluid in chamber:	63	ml						
Time	Measured KBAT Transducer Pressure	Volume of H2O in KBAT Chamber	Height of H2O in KBAT chamber from Mid. Filt. h'	a = H + Patm/gamm a - h'	K1	K2	Velocity of flow through Swagelok valve v=Q/A	Reynold's Number R for flo through Swagelok valve	Head Loss due to flow through Swagelok valve
(sec)	(m H2O)	(mL)	(m)	(N/m)	(m/s)	(m/s)	(m/s)	(dim. less)	(m)
0.0	8.40	98.0	0.52	14.71					
1.6	7.54	90.3	0.51	14.72	#VALUE!	#VALUE!	2.5E-01	925	0.002
3.2	7.17	86.8	0.50	14.72	#VALUE!	#VALUE!	1.3E-01	461	0.001
4.8	6.96	84.8	0.50	14.73	#VALUE!	#VALUE!	7.7E-02	283	0.000
6.4	6.82	83.3	0.50	14.73	2.1E-06	1.7E-06	7.2E-02	266	0.000
8.0	6.65	81.5	0.49	14.73	1.4E-06	1.3E-06	5.4E-02	199	0.000
9.6	6.59	80.9	0.49	14.73	1.2E-06	1.2E-06	4.9E-02	182	0.000
11.2	6.44	79.3	0.49	14.73	1.1E-06	1.1E-06	4.7E-02	173	0.000
12.8	6.39	78.8	0.49	14.74	1.1E-06	1.1E-06	4.1E-02	151	0.000
14.4	6.26	77.5	0.49	14.74	9.7E-07	9.5E-07	5.9E-02	219	0.000
16.0	6.14	76.2	0.49	14.74	1.2E-06	1.1E-06	3.9E-02	144	0.000
17.6	6.10	75.7	0.49	14.74	1.0E-06	1.0E-06	3.7E-02	135	0.000
19.2	6.00	74.5	0.48	14.74	1.2E-06	1.1E-06	3.4E-02	124	0.000
20.8	5.97	74.2	0.48	14.74	1.1E-06	1.1E-06	4.1E-02	152	0.000
22.4	5.83	72.7	0.48	14.75	1.1E-06	1.1E-06	4.2E-02	155	0.000
24.0	5.80	72.4	0.48	14.75	1.1E-06	1.1E-06	3.0E-02	112	0.000
25.6	5.71	71.3	0.48	14.75	1.0E-06	1.0E-06	3.6E-02	131	0.000
27.2	5.67	70.8	0.48	14.75	1.1E-06	1.1E-06	3.3E-02	121	0.000
28.8	5.59	69.9	0.48	14.75	1.1E-06	1.0E-06	3.2E-02	119	0.000
30.4	5.54	69.3	0.48	14.75	1.1E-06	1.0E-06	1.9E-02	70	0.000
32.0	5.52	69.0	0.48	14.75	1.0E-06	1.0E-06	1.6E-02	57	0.000
33.6	5.48	68.6	0.47	14.75	1.1E-06	1.1E-06	3.1E-02	114	0.000
35.2	5.40	67.6	0.47	14.75	9.2E-07	8.9E-07	2.5E-02	91	0.000
36.8	5.39	67.5	0.47	14.75	1.1E-06	1.1E-06	1.7E-02	63	0.000

FIGURE 2. Example of KBAT Outflow Spreadsheet

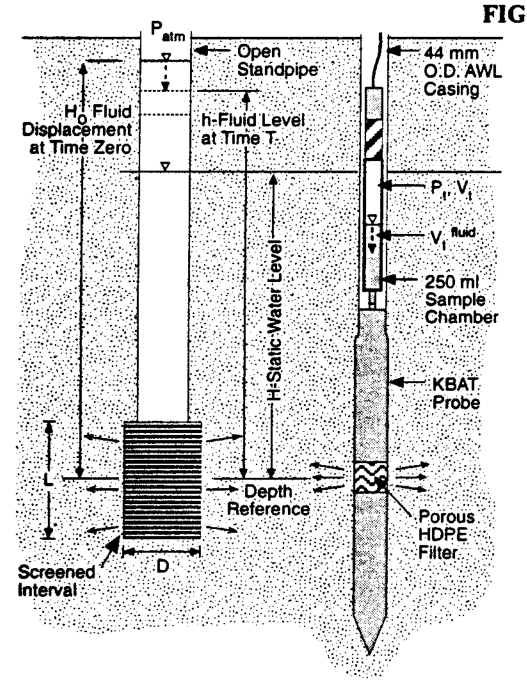


FIGURE 5. Schematic Illustration of Open Standpipe Falling Head Test and Modified KBAT Outflow Test.

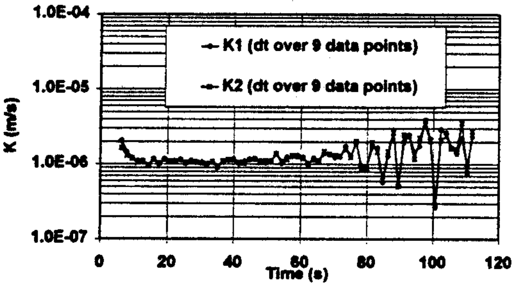


FIGURE 3. KBAT Test Results - Outflow Test, Massey Tunnel M9603CPT, Depth = 8.22m

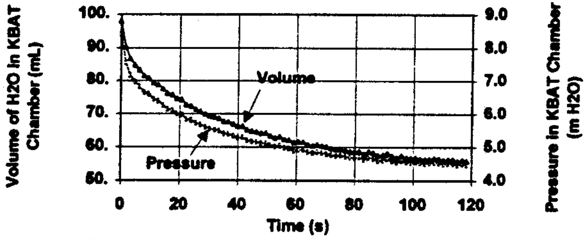


FIGURE 4. KBAT Test Chamber Pressure and Volume - Outflow Test, Massey Tunnel M9603CPT, Depth = 8.22m

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