Constant-Head Permeability Tests Performed in Monitoring Wells at Laboratory Scale

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Lu Zhang, Robert P. Chapuis & Vahid Marefat
Department CGM, Ecole Polytechnique, Montreal, Quebec, Canada

ABSTRACT
Two types of permeability tests have been performed in ten wells monitoring a confined aquifer, installed in a large sand box. Electronic transducers have been used to register total pressure and atmospheric pressure versus time. The paper presents first the method used to calibrate the sensors, in order to assess their zero offset and its influence on the test data. Then, it presents the results of the variable-head tests and those of constant-head tests performed using a peristaltic pump, thus as constant flow rate tests until stabilization of the water level in the well riser pipe. In addition, several types of constant-head tests have been performed: (i) single flow rate as for groundwater sampling; (ii) different flow rates, with or without rest periods between the periods of constant flow rate. The paper presents and discusses the hydraulic conductivity values that have been obtained from the field data for each type of test, and the influence of seepage direction through the slots of screens having a low open area.

RÉSUMÉ
Deux types d'essais de perméabilité ont été réalisés dans dix puits de surveillance d'un aquifère à nappe captive, dans une grande cuve de sable. Des capteurs électroniques ont été utilisés pour enregistrer la pression totale et la pression atmosphérique en fonction du temps. L'article présente d'abord la méthode utilisée pour calibrer les capteurs, de façon à évaluer l'erreur sur leur zéro et son influence sur les données d'essai. Il présente ensuite les résultats des essais à niveau variable et ceux des essais à niveau constant, réalisés avec une pompe péristaltique, donc comme des essais à débit constant jusqu'à stabilisation du niveau d'eau dans le tuyau du puits. De plus, différents types d'essais à niveau constant ont été réalisés : (i) débit unique comme pour un échantillonnage; (ii) plusieurs débits, avec ou sans période de récupération entre les étapes à débit constant. L'article présente et discute les valeurs de conductivité hydraulique obtenues des données d'essais in situ pour chaque type d'essai, et l'influence de la direction de l'écoulement dans les fentes des crépines de faible surface ouverte.

1 INTRODUCTION

The hydraulic properties of confined aquifers are critical for many hydrogeological and geotechnical problems. The hydraulic conductivity *k* may be assessed by several types of field permeability tests, which may provide different values. Monitoring wells installed in a large sand-box are used herein to compare the *k* values of a confined aquifer obtained by four methods: variable-head test, constant-head permeability test and step-drawdown test with or without rest between the pumping steps. All tests are performed within a saturated material where the pore water pressure is greater than the atmospheric pressure. The step-drawdown tests are regularly used to assess the well installation performance, but in this paper they are used to obtain other *k* values to make comparisons. Step-drawdown tests are also frequently used for groundwater sampling.

For all tests, the water level position versus time has been registered by a pressure transducer (PT) and an atmospheric pressure transducer (APT). The drawdown for a pumping test and the change in water column for a permeability test, are often obtained by the following direct subtraction: current PT reading at current time *t* minus the initial PT reading for the water level at rest before the test. However, this direct subtraction does not take into account the change in air pressure during the test.

This paper examines how this change in barometric pressure, during a test, influences the test data accuracy and the resulting *k* value. This paper first describes the calibration method for different pairs of PTs and APTs to assess their accuracy and then, it examines the influence of a variable barometric pressure.

The variable-head permeability tests were started with a water level sudden change in the well riser casing by quick insertion or discharge of water, and the subsequent water level response was recorded over time. The falling-head test was conducted with an extension transparent tube added on the top of the well riser casing. The PT and APT were synchronized and programmed to take readings with a 2-seconds interval because the water recovery was rapid. The variable-head test data were analyzed using the method of Hvorslev (1951) and the velocity graph method (Chapuis, 1998).

The constant-head permeability tests were performed by pumping at a constant rate using a peristaltic pump, and registering the water level position versus time. The step-drawdown tests have used several constant pumping rates, which were either successive or separated by rest periods to return to initial equilibrium. The step-drawdown test data were analyzed using the method of Lefranc to obtain the *k* values. The different *k* obtained with different testing methods are compared and discussed.

2 MATERIALS AND METHODS

2.1 Test materials

Small monitoring wells have been installed in the sand tank which consists of three layers: unconfined sand aquifer, sand-bentonite aquitard, and confined sand aquifer. Each layer has been prepared to be fairly homogeneous and isotropic, thus expected to yield little variations in hydraulic properties.

The stainless steel sand box tank is 3.05 m long, 2.44 m wide, and 1.22 m high. It contains, from the bottom to the top, a 38 cm thick confined sand aquifer, a 20 cm thick aquitard, and a 50 cm thick unconfined sand aquifer. The two ends of each aquifer are coarse sand around full width slotted plastic pipes connected to reservoirs. There are four constant head reservoirs. Depending on the imposed heads in these reservoirs, each aquifer can be tested under no gradient or a constant horizontal gradient.

The same uniform sand was used for the two aquifers. Its sizes d_{10} and d_{60} are 0.116 and 0.46 mm, respectively, and thus, the coefficient of uniformity $C_U = d_{60}/d_{10} = 4$. In the confined aquifer the sand was statically compacted with light loads: its average dry density is 1640 kg/m^3. The aquitard material is a sand-bentonite mix that contains 8% bentonite, with increased bentonite content along the walls to provide a good seal by taking advantage of its swelling capacity.

This paper presents results for ten monitoring wells installed in the confined aquifer. These monitoring wells have 15 cm long screens that begin at 11.3 cm from the steel bottom. The pipes have an internal diameter of 33.8 mm, and an external diameter of 42.5 mm. They were buried in the sand during its placement and developed by slight overpumping. Their slots are 0.25 mm wide, and their open area is about 2%. For performing falling-head tests, an extension tube of internal diameter 28 mm was used above the riser pipe.

A pressure transducer (PT) is an accurate and efficient tool to monitor the fluctuations with time of a groundwater level. It usually measures the total pressure acting on its sensor. To obtain the true water column height above the sensor, the barometric pressure taken by an atmospheric pressure transducer (APT) should be subtracted from the PT reading. Four different models of pressure transducers have been used for the test program reported in this paper. The reading interval for the constant-head permeability test and step drawdown test was 15 seconds. For the variable-head tests, the reading interval was 2 seconds.

2.2 Calibration

For pumping tests, it is considered that the air pressure should be measured if the test lasts one or more days (Kruseman and de Ridder 1991). This means that the PT readings must be corrected for an atmospheric pressure which varies with time, APT (t). However, many users of PTs and APTs make only a single correction from an initial APT reading, which is incorrect, and yields errors on the water level data for the monitoring well. In the tests of this paper, the air pressure in the laboratory (which differs from the outside atmospheric pressure) was always taken into account because a fluctuation of a few centimetres may have a significant impact on the water level data.

The accuracy of PTs is usually 0.1% and rarely 0.05% FS (full scale). If FS is 3 m, then the PT accuracy is ±3 mm or ±1.5 mm. The APT accuracy is usually ±5 mm. The ensuing accuracy for the water column (PT–APT) is thus ± 8 mm or ±6.5 mm. However, these are theoretical values. The PT and APT were not calibrated as the same time in the plant. Also, the air pressure within the plant is controlled by the outside atmospheric pressure and also ventilation and air conditioning. Therefore, it differs from the outside atmospheric pressure. As a result, if the (PT–APT) difference is checked in the air, for example at the user's desk, a non null value between -10 cm and +10 cm is found (most usual range), whereas the difference should be zero because there is no water column above the PT on the user's desk (Chapuis 2009). This was confirmed by Sorensen and Butcher (2011), and Von Asmuth et al. (2008). As a result, most often the physical water column height is known with an accuracy of ±8 mm or ±6.5 mm (random error) for a (PT–APT) pair, but with a much larger systematic error of ±10 cm, or even ±30 cm. In addition to previous errors, the APT may be incorrectly compensated for temperature variation, which is important for long duration slug tests in aquitards (Cain et al. 2004; McLaughlin and Cohen 2011). The resulting accuracy and the systematic error should be taken into account in any analysis of slug test data or drawdown data.

In this paper, we define the systematic piezometric error as δ_0 as the mean value of [PT(t) – APT(t)]. To ensure the accuracy of analysis for groundwater field tests, this systematic error should be known and thus, the calibration of each pair (PT, APT) is necessary. Five types of PTs and APTs have been used, and renamed A, AA, B, C, D, respectively, to avoid citing commercial names. The full scale (FS) range varies between 1.5 and 10 m, and the accuracy is 0.1% or 0.05%.

2.3 Variable Head Test

The variable head tests were performed as falling-head tests. The initial slug was obtained by quickly injecting water into the monitoring well. Such tests in the large sand box have already been reported by Chapuis and Chenaf (2002), and used to show that one theory, which involves storativity, did not provide good estimates for the *k* value, when compared to pumping tests, and also when compared for uniform seepage under a constant gradient within the confined aquifer. As a result, the solution of Hvorslev (1951) and the velocity graph method (Chapuis et al. 1981) have been used to interpret the variable head data. The velocity graph method has given the systematic error H_0, if any, that was done on the assumed piezometric level used in the Hvorslev's method. The test experimental data were therefore interpreted using the Canadian standards (CAN/BNQ 1988, 2008).

The classical equations for a variable-head test simply write that the flow rate in the soil (Q_{soil}) is equal to the flow rate into the pipe (Q_{inj}):

$$Q_{inj} = Q_{soil} = ckH \qquad [1]$$

where c is the test shape factor, H the water column or applied hydraulic head difference, and k the hydraulic conductivity. The riser pipe, of inner diameter d, has an internal cross section area $S_{inj} = \pi d^2/4$ and the water velocity in the riser pipe is dH/dt. Thus:

$$Q_{inj} = -S_{inj} \frac{dH}{dt}. \quad [2]$$

Combining equations [1] and [2] gives:

$$\frac{dH}{dt} = -\frac{ckH}{S_{inj}}. \quad [3]$$

Integrating leads to Hvorslev's solution, in which the hydraulic head is generally in a logarithmic form:

$$\ln\left(\frac{H_1}{H_2}\right) = -\frac{ck}{S_{inj}}(t_1 - t_2) = -\frac{k}{C}(t_1 - t_2), \quad [4]$$

where H_1 and H_2 are the total head at times t_1 and t_2, respectively and $C = S_{inj}/c$.

The test data are plotted as ln H on the y-axis and time t on the x-axis in the Hvorslev's graph. If the test is good, the data should yield a straight-line. Then, according to equation [4], the slope of the straight line should be:

$$P_1 = -\frac{\ln(H_1) - \ln(H_2)}{t_1 - t_2} = \frac{\ln(H_1/H_2)}{t_1 - t_2} = -\frac{k}{C}. \quad [5]$$

Therefore,

$$k = P_1 C. \quad [6]$$

The velocity graph method uses directly Eq. [3] and has been verified to be correct in estimating the real piezometric level (PL) and the hydraulic conductivity k (Chapuis et al. 1981; Chapuis 1998, 2001, 2015) by plotting the water level velocity $\Delta H/\Delta t$ in the pipe versus the mean value of the assumed difference in hydraulic head $(H_i+H_{i+1})/2$.

According to Eq. [3], the plotted data of velocity during a time interval dt versus the mean H value during the same time interval should yield a straight line. The true H value is frequently not accurately known, and the real value H_r, is the difference between the H value assumed by the user, and the error on the piezometric level H_0, which may result from several sources of errors, including the PT and APT incorrect calibrations (Chapuis 2009):

$$H_r = H - H_0. \quad [7]$$

Combining Eqs. [3] and [7] yields:

$$H = -\frac{S_{inj}}{ck}\frac{dH}{dt} + H_0. \quad [8]$$

Thus Eq. [8] should yield a straight line with a slope of:

$$P_2 = \frac{S_{inj}}{ck} = \frac{C}{k}. \quad [9]$$

Therefore

$$k = \frac{C}{P_2}. \quad [10]$$

Then, once the real piezometric level for the test has been found with the velocity graph, the Hvorslev's method (the integral of the velocity graph method) can be used to confirm the previously found K value.

For the field permeability tests performed with monitoring wells in the large sand box, the ratio of the lantern length to its diameter is L/D = 15 cm / 4.25 cm = 3.53, is in the range of $1 \leqslant L/D \leqslant 8$, for which the shape factor is given by:

$$c = 2\pi D\sqrt{\left(\frac{L}{D} + \frac{1}{4}\right)}. \quad [11]$$

2.4 Constant-Head Tests

The constant-head tests were performed by pumping or injecting a single constant flow rate from or into the riser pipe until reaching a stable water level. After the pump stopped, the water level in the riser pipe slowly returned to the pre-test static water level. The pumping rate was 100 ml/min, and 10 minutes were allowed for recovery. The PT registered the water level every 15 seconds during the test, and the APT recorded the air pressure change synchronously to provide accurate data for water levels.

The step-drawdown tests started with a low pumping rate until the drawdown stabilizes, and then the pumping rate was increased to a higher constant value to make the next step. At least, three steps are needed (Kruseman and de Ridder 1991). Two types of step-drawdown tests, both with three steps, were conducted, one with rest periods (for water level to recover) and the other without rest between the steps. The discharge rates of the three steps were initially 100-200-300 cm^3/min for monitoring wells PB19 and PB20, and then reduced to 50-100-150 ml/min for PB8, PB18, and PB22. The former tests had step durations of 30, 60 and 90 min, and rest periods of 10, 20 and 30 min respectively (if there were rests), whereas the latter tests had all the same duration of 30 min for a pumping step and 10 min for a rest period, with the result of shortening the test duration.

All discharge rates were automatically controlled by the peristaltic pump. However, because the real rate may slightly differ from the one displayed by the pump, the real pumping rate was controlled using a burette and a stopwatch during the test.

For the constant-head test, the hydraulic conductivity is obtained using Eq. [1]:

$$k = \frac{Q}{cH_c}. \quad [12]$$

In Eq [12], Q is the discharge rate or pumping rate, c is the previously defined shape factor and H_C is the constant head difference between two positions of the water level in the monitoring well, one at rest before the test and the other after stabilization during pumping. In the step-drawdown test with rest periods, H_C is the difference between the stabilized water level for one step and the previous recovered water level. Thus, three head differences and three hydraulic conductivities are obtained for each step-drawdown test.

3 RESULTS AND DISCUSSIONS

3.1 Calibration

3.1.1 Systematic Error

The difference between the PT and APT data at time t, thus [PT*(t)* – APT*(t)*], were calculated for each pair of PT and APT. A representative example of this difference with the two transducers in the air (on a desk) is plotted in Figure 1, to assess the systematic error for this pair of transducers. For this pair, the systematic error, δ_0, which is the mean value of [PT*(t)* – APT*(t)*], is -4.6 ± 0.5 cm.

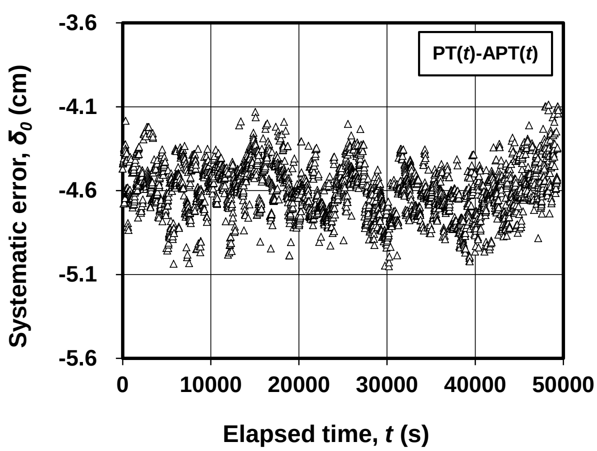

Figure 1. Example of [PT*(t)* – APT*(t)*] data for a pair of transducers.

For the *A* series of three transducers, the errors δ_0 were -2.7, -7.7 and -11.3 cm. These errors were found to be stable with time. The errors δ_0 of the *AA* series were between -2.8 cm and -1.3 cm. For the *B* series, the errors δ_0 were between -3.4 cm and 0 cm, but they took initially some time to decline gradually to a stable level with a random fluctuation of ±1 cm. For the *C* series, the errors δ_0 were nearly stable with time. For most transducers of the *C* series the error δ_0 was between -2.9 cm and +7.6 cm, except for C_3 which had an error δ_0 of +17.2 cm. These transducers were not used for the tests reported in this paper. For the *D* series, the errors δ_0 were roughly stable with time, and they were between -5.7 and +4.0 cm.

The examples of errors which have been previously given are for pairs made with only one barometric transducer. It is reminded here that a correction must be defined for each pair formed by a PT and an APT.

3.1.2 Test Protocol

For a constant-head permeability test, two pressure transducers were installed to record the different water levels and their variation with time. The first PT was installed inside the MW riser pipe, whereas the second PT was installed in the recharge pipe, in order to verify its constant water level throughout the test. If the pumping rate in the MW exceeds the overflow at the recharge boundary, the recharge boundary is no longer a constant head boundary, which would modify the interpretation of the constant-head permeability test in the MW.

For constant- and variable-head tests, the water level change within the MW riser pipe was monitored with a pressure transducer. The apparent water column for the test, at a time t, is H(t), whereas the really active water column is H_r(t), the two being related by:

$$PT(t) - APT(t) = H(t) = H_r(t) + \delta_0 \qquad [13]$$

The smaller the systematic error of the (PT-APT) pair, the better the test data. It is clear that to ensure the accuracy of the test data, a barometric transducer is of significant necessity for any field permeability test. In other words, the systematic error of the pair of transducers should be subtracted from the original results, in order to obtain the really active water column.

3.2 Variable-Head Test

Two values of k were calculated, one by the Hvorslev's method and one by the velocity method, for ten monitoring wells of the confined aquifer. Here, we only present one set of test data, for monitoring well PB8, in Table 1, and the relationship between the mean value of H during a time interval (as defined in Eq. 14) versus the water velocity during this time interval, and the relationship between ln (H_r) and the elapsed time in Figure 2.

$$\text{Mean } H \text{ between } t_i \text{ and } t_{i+1} = 0.5\,[H(t_i) + H(t_{i+1})] \qquad [14]$$

For all tested monitoring wells, the two interpretation methods yielded only small differences in k values, which will be discussed in section 3.5. Also, for all variable-head tests, the velocity graph was found to be straight, and not smoothly curves as predicted by other theories using a physically incorrect equation with the storativity (Chapuis 1998; Chapuis and Chenaf 2002).

3.3 Constant-Head Test

Constant-head pumping tests were performed in ten monitoring wells of the confined aquifer. Two sets of test data versus time t are plotted in Figure 3 for monitoring well PB8. One plot gives the variation in total pressure, as registered by the PT, thus the sum of water column plus atmospheric pressure, between 1094 and 1104 cm of water (see the right ordinate, for the plot ending near 1102 cm). According to Eq. 13, we have:

$$PT(t) = H(t) + APT(t) \quad [15]$$

The same plot can also be read with the left ordinate as the calculated variation in water column, when a single barometric correction is used (lower curve), which is:

$$H(t) = PT(t) - APT(t) \quad [16]$$

This graph with two ordinates can be plotted because $H(t)$ and PT(t) differ only by the APT which is changing with time. As mentioned before, according to experience, many users of PTs and APTs make a single barometric correction (e.g., some pre-test APT value) for field permeability tests, which is incorrect.

Usually, the atmospheric pressure varies with time. This is why the theoretically more correct second plot is also plotted in Figure 3. It gives [$PT(t)$ – $APT(t)$], expressed in cm of water, thus the real water column, in which the atmospheric pressure varies with time.

Table 1. Variable test data recorded by the pressure sensor for PB8.

Elapsed time t (s)	Interval Δt (s)	Water column H (cm)	Variation ΔH (cm)	Mean H $(H_i+H_{i+1})/2$ (cm)	$\Delta H/\Delta t$ (cm/s)	$H_r = H - H_0$ (cm)	ln (H_r)
0		74.1				65.3	4.18
2	2	64.0	10.1	69.05	5.05	55.2	4.01
4	2	55.8	8.2	59.90	4.10	47.0	3.85
6	2	48.7	7.1	52.25	3.55	39.9	3.69
8	2	42.8	5.9	45.75	2.95	34.0	3.53
10	2	37.6	5.2	40.20	2.60	28.8	3.36
12	2	33.1	4.5	35.35	2.25	24.3	3.19
14	2	29.6	3.5	31.35	1.75	20.8	3.03
16	2	26.4	3.2	28.00	1.60	17.6	2.87
20	4	21.5	4.9	23.95	1.22	12.7	2.54
24	4	17.6	3.9	19.55	0.98	8.8	2.17
30	6	14.1	3.5	15.85	0.58	5.3	1.67

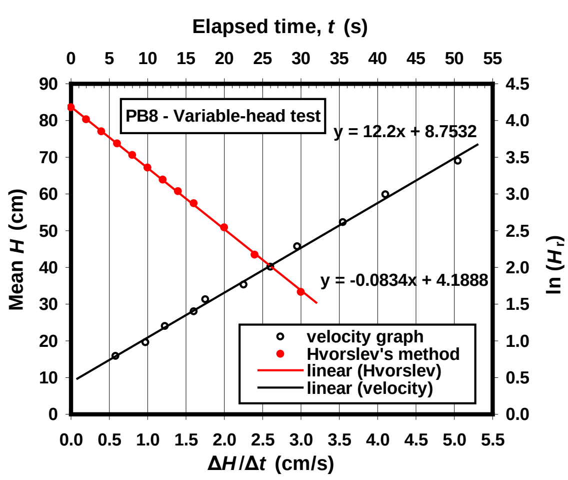

Figure 2. Hvorslev's method and velocity graph method for a variable-head test in monitoring well PB8.

In Figure 3, it is clear that the total water pressure (including barometric pressure) is around 1104 cm before starting the test, whereas it is about 1102 cm after the test, 2 cm below the pre-test value. However, physically, it was verified, with a measuring tape, that the water level in the monitoring well had returned to its initial position. Therefore, the plot means that the atmospheric pressure (APT) has varied by about 2 cm during the test.

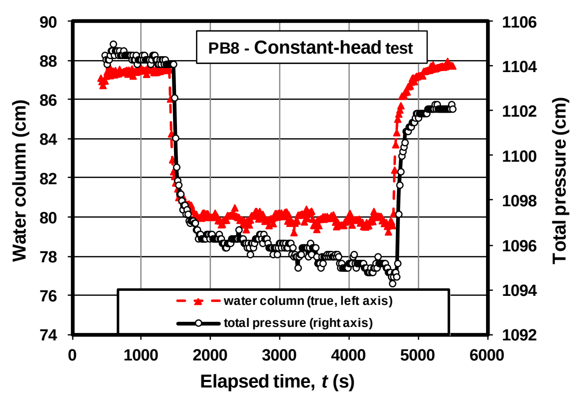

Figure 3. Total pressure and water columns (real and approximate) for a constant-head test.

When the constant-rate pumping started, the water level rapidly dropped by about 9 cm in about 4 minutes, as shown in the total pressure curve, and then seemed to slowly decrease with time until the end of pumping at 4600 seconds. Apparently, this "constant-head" test never reached stabilization, i.e. a constant drawdown. This conclusion would be incorrect because the atmospheric pressure variation of 2 cm of water is responsible for this apparent decline in water level between 1800 and 4600 seconds.

The [*PT*(*t*) – *APT*(*t*)] plot, in which the atmospheric correction varies with time helps to draw a different conclusion: the water column has stabilized rapidly, 4-5 minutes after starting the constant-rate pumping. The water column was constant before and after the test at approximately 87.5 cm, and it has stabilized at about 80 cm while pumping.

This example clearly shows that using a PT without a barometric correction which varies with time, may yield errors in interpreting the data of a constant-head test. For the example in Figure 3, one may consider that the test was incomplete because there was a declining trend in the water column. This may be misinterpreted, for example, as a need to have had a longer duration test.

After a long pumping time, e.g., during groundwater sampling in the monitoring well, the water column given by Eq. 16 may stabilize, simply because the atmospheric pressure decreased and finally stabilized, for example 15 cm below that prevailing before the test. However, if this change in atmospheric pressure is ignored, the calculated *k* value is erroneous. For the case of Figure 3, the true stabilized drawdown is about 7.5 cm, but an incessant change in atmospheric pressure of 15 cm would yield an apparently stabilized drawdown of (7.5 + 15) cm, an error of 300% for the stabilized drawdown, thus a 300% error on the calculated *k* value. This simple example, which may occur during a groundwater sampling test, is illustrating that we need to pay more attention to the importance of correction for the atmospheric pressure.

3.4 Step-Drawdown Test

The typical use of step-drawdown tests is to evaluate the performance of a pumping well whereas, in this paper, it is treated as a type of constant-head test. The constant discharge rate and drawdown at the end of each step is used to calculate *k*.

The water column changes, obtained with the APT(*t*) values, appear in Figs 4-5 for monitoring well PB22. Figure 4 is for the test with recovery periods between pumping steps (3 constant pumping rates were used), whereas Figure 5 is for a test in the same monitoring well, but without rest periods. The resulting k values obtained from each step are listed in Table 2.

In Figure 4, the three constant pumping rates are 50, 100, and 150 cm^3/min. The initial and recovered water columns are nearly equal, and during each pumping step the water column rapidly stabilizes, but with erratic fluctuations, which increase with the pumping rate. In theory, if the monitoring well is well installed and has no parasitic head losses in the screen and filter pack (e.g., Todd 1980; Baptiste and Chapuis 2015) the water drawdown for the three steps should be increased by a same value because the constant discharge rate is also increased by a constant value of 50 cm^3/min. In the case of Figure 4, the water drawdowns for the three steps are about 2.4, 5.0, and 7.6 cm. This leads to a nearly constant *k* value, with a very small *k* increase for increased *Q*.

In Figure 5, the stabilized drawdowns for the three pumping rates are 2.7, 5.0, and 7.9 cm, which are close to theory, but they are probably influenced by several inaccuracies. The difference between measurement and theory may be caused by the intrinsic inaccuracy of the PT and APT (for example ± 3 mm of water), some small fluctuation in the pumping rate, with resulting changes in water pressure which are registered by the pressure transducer, and also the entry of some air in the pumping pipe during pumping.

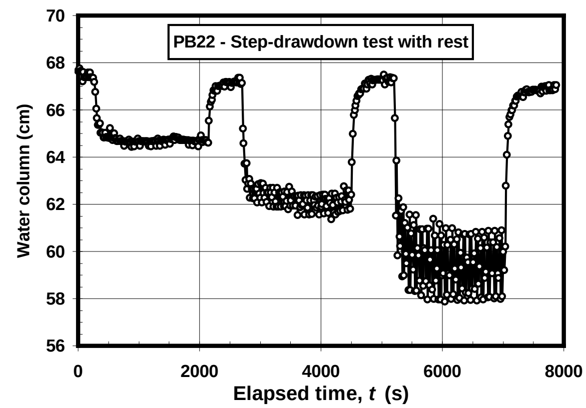

Figure 4. Recorded water column for a step-drawdown test with rest periods (recovery).

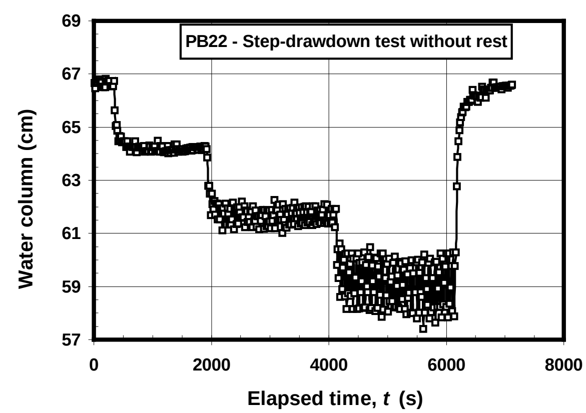

Figure 5. Recorded water column for a step-drawdown test without rest periods.

Figures 4 and 5 clearly show the erratic fluctuations of “stabilized” drawdowns. These are approximately 0.5, 1.0, and 3 cm for discharge rates of 50, 100, 150 cm^3/min, respectively. The peristaltic pump sucks water with a small-diameter pipe and a deep small-diameter water intake, which has been attached to the well-riser pipe, to reduce vibrations during pumping. However, an increase in pumped flow rate results in increased vibration of the pipe and water intake piece, which is probably the reason for the fluctuations in water pressure that are registered by the pressure transducer (PT) in the monitoring well.

Table 2. Hydraulic conductivity calculated by variable-head, constant-head and step-drawdown tests.

Monitoring Well	Variable-head test		Constant-head test	step-drawdown, no rest			Step-drawdown, with rest		
	Velocity Graph	Hvorslev's Method		Q1	Q2	Q3	Q1	Q2	Q3
PB8	9.75E-05	9.92E-05	4.54E-05	6.17E-05	5.84E-05	5.41E-05	5.54E-05	5.54E-05	5.47E-05
PB15	1.16E-04	1.16E-04	5.00E-05						
PB16	1.16E-04	1.22E-04	5.62E-05						
PB17	9.99E-05	1.00E-04	5.21E-05						
PB18	1.13E-04	1.12E-04	5.13E-05	6.98E-05	6.30E-05	5.80E-05	6.98E-05	5.95E-05	5.41E-05
PB19	8.91E-05	9.08E-05	4.46E-05				4.60E-05	4.64E-05	3.97E-05
PB20	9.73E-05	9.94E-05	4.71E-05	5.54E-05	5.19E-05	4.60E-05	5.33E-05	4.05E-05	3.84E-05
PB21	9.16E-05	9.30E-05	5.08E-05						
PB22	1.04E-04	1.05E-04	6.08E-05	6.69E-05	6.42E-05	6.34E-05	5.85E-05	6.65E-05	6.22E-05
PB23	7.88E-05	8.04E-05	5.00E-05						

3.5 Comparison of *k* values

For each monitoring well, 2, 3 or 4 testing methods have been used. In addition, the variable-head tests were interpreted using two methods (Hvorslev and velocity graph), and each step-drawdown test (with or without rest periods) provided three *k* values, one for each constant pumping rate. As a result, three to nine different *k* values were obtained for each monitoring well.

The *k* values obtained by falling-head tests and using the Hvorslev's method and the velocity graph method were always close for each monitoring well. However, they were about 2 times greater than the k value obtained with constant-head tests or step-drawdown tests. The major physical difference between the two types of tests is only that of the water movement within the slots of the screen. Screens with small slot sizes (0.254 mm), and small open area of 3.56%, have been installed in the sand box, and carefully backfilled with sand compacted in layers 5 cm thick. The small open are of such screens has the capacity to alter the *k* value of field permeability and pumping tests (Baptiste and Chapuis 2015). During a falling-head test, the outward water pushes away some sand grains which were partially clogging the screen slots, which facilitates seepage and results in a high *k* value. During a constant-head or step-drawdown pumping test, the inward water pushed the sand grains against the thin screen slots, which maintains partial slot clogging and results in a low *k* values. More sophisticated tests will be needed to document this phenomenon.

The step-drawdown pumping tests and the constant-head permeability test have used the same interpretation method. The *k* values given by the two methods were slightly different, by about 5 to 25%, which is a small difference for field permeability tests. In addition, it was found (see Table 2) that an increased pumping rate caused a small decrease in *k*. This result means that all monitoring wells are imperfect, probably because their plastic screens have a too small open area. Their imperfection results in parasitic head losses which increase with the pumped rate (Todd. 1980), and artificially yield a decreasing *k* value when the parasitic head loses are not properly taken into account. Also, more air may enter into the pumped water, and the water column, which may modify and then reduces the calculated *k*. This possibility has also to be investigated with different pumping systems and more sophisticated tests.

However, and this important for field tests and practical purposes, it was found that the step-drawdown tests give the same results for tests with or without rest periods. In practice, for field tests, it means that the tests can be performed without using rest periods to let the water level return to its equilibrium position.

Another strong practical result is that the different constant-head methods yielded nearly equal *k* values for each monitoring well. Therefore, all testing methods have been found to be equally reliable. For example, the constant-head pumping tests gave an average *k* of 5.1 x 10^{-5} m/s for the confined aquifer. The highest *k* value is 6.1 x 10^{-5} m/s at PB22 and 20% higher than the average *k* value. The lowest *k* value is 4.46 x 10^{-5} m/s for PB19, 12.2% lower than the average *k* value. Therefore, the confined sand aquifer appears to be homogeneous, which is an essential condition for a research project.

4 CONCLUSION

When a pressure transducer (PT) and an atmospheric pressure transducer (APT) are in the air, the difference [PT(*t*) – APT(*t*)] should be zero in theory, and it should not vary with time *t*. A plot of this quantity versus time should yield a mean value of zero and the fluctuations around zero should give the accuracy of this (PT, APT) pair. In practice, however, the mean difference is rarely zero.

For the project of this paper, five different types of PTs (for a total of 32 PTs) were verified using a single APT pressure sensor. The 32 pairs yielded a difference which was not equal to zero. The calibration yielded a zero calibration error between -11 and +17 cm. This error produces a systematic error for the measured values of all water columns which are used to calculate the *k* value as given by a field permeability test.

A simple test protocol (transducers in the air on the desk or in the truck) is needed to assess the systematic error and the (PT, APT) pair accuracy. Each PT user must first select the appropriate range of measurement, for example 0-3m for a field permeability test. The systematic error of the (PT, APT) pair must be documented to obtain the calibration error and the (PT, APT) pair accuracy.

The correction for air pressure should not be done with a single APT value for some pre-test time. The air pressure varies continuously during any field hydraulic test (or even laboratory test). Therefore, the PT and APT must be synchronised, in order to take data at the same time. These data are then used in the following difference [PT(t) – APT(t)] where the barometric correction varies with time t. This procedure is essential to obtain reliable test data before doing any data interpretation.

An example has been given to show the important influence of the air pressure variation within the laboratory (air conditioning and ventilation) during a constant-head permeability test. Thus, it was important to use the APT synchronously with the pressure transducer.

For the testing program of this paper, it was found that the Hvorslev's method and the velocity method provided close values for k. However, the falling-head tests gave higher k values than the constant-head tests and step-drawdown tests. The difference is believed to be due to the small open area of the screens, and to the opposite directions of water within the screen slots. These physical aspects also influence parasitic head losses in the screen and at the screen-aquifer interface. This produced a small reduction in the apparent k when the pumping rate was increased, which is conform to the theory of parasitic head losses for pumping wells.

Finally, it is not necessary, when performing step-drawdown tests as constant-head tests, to have a rest period (let the water level to return to the pre-test equilibrium level) between two constant pumping rates.

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