Interpretation of falling-head tests performed on low hydraulic conductivity soils

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ABSTRACT
A review of interpretation methods for falling-head tests is presented. The statistical robustness of each method is then evaluated through the use of synthetic data. Six datasets are used for this evaluation. Each dataset has an absolute error in Z respectively of 0.10, 0.25, 0.50, 0.75, 1.00 and 2.00 mm. Each dataset is composed of 40 synthetic tests (each test consisting of 18 data couples of synthetic falling-head measurements). Results show that the most accurate and precise method is the Z-t one, followed by corrected Hvorslev and alternate velocity. The velocity method is found to be the worst of the four studied methods. It should thus only be used when data scatter in the velocity plot is negligible, that is when both Z-t and velocity methods give comparable results.

RÉSUMÉ
Un examen des méthodes d'interprétation des essais à charge-variable est présenté. La robustesse statistique de chaque méthode est ensuite évaluée à l'aide de mesures synthétiques. Six ensembles de mesures sont utilisés dans cet examen.Chaque ensemble a une erreur absolue Δ_Z respectivement de 0.10, 0,25, 0,50, 0,75, 1,00 et 2,00 mm. Chaque ensemble est composé de 40 essais synthétiques (chaque essai consistant de 18 couples de données de mesures synthétiques de charges descendantes). Les résultats montrent que la méthode la plus exacte et précise est la Z-t, suivi de Hvorslev corrigé et puis de la méthode alternative des vitesses. La méthode des vitesses est la moins performante des quatre méthodes étudiées. Elle doit donc seulement être employée lorsque les points du graphe des vitesses sont sans dispersion. Ceci sera le cas lorsque la méthode Z-t et celle des vitesses donnent des résultats comparables.

1 INTRODUCTION

A number of methods exist to measure saturated hydraulic conductivity of soils. The constant head test (ASTM 2008) is one of these methods. In a laboratory setting, water inlet and outlet need to be maintained at constant elevations. Measurements of water flow rate in function of hydraulic gradient (head loss per flow path distance) allow the computation of the hydraulic conductivity of the soil using the following equation:

$$k = -\frac{QL}{(h_2 - h_1)A} \qquad [1]$$

where Q is the flow rate, L is the distance separating the piezometer measuring tips, h_j are measured heads at measuring tips 1 and 2 and A is cross-section of the permeameter. ASTM (2008) is a good source for permeameter design and testing procedures. When performing hydraulic conductivity tests in the laboratory, Chapuis et al. (1989) stress the importance of good saturation. They describe a testing protocol to reach and measure saturation levels of tested samples.

Constant head tests can also be performed in the field. CAN/BNQ (1988a and b) describe methods where water is injected in a cased borehole at a constant head in an aquifer under steady state conditions. Hydraulic conductivity can then be computed by using:

$$k = -\frac{Q}{C(h_2 - h_1)} \qquad [2]$$

where C is a shape factor that is for example 2.75 times the inner diameter D for the case of an end of casing test, h_1 is the total head of water in the cased borehole, h_2 is the total head at the aquifer free surface (or piezometric level of aquifer). This method is based on the hypothesis that the injected volume of water will have negligible influence on the piezometric level (PL) of the soil surrounding the injection zone.

When testing low hydraulic conductivity soils, the main drawbacks of constant head tests are that they are extremely lengthy in time and in the case of field tests, the PL of the soil layer may be unknown or difficult to measure. Falling-head tests are effective answers to both these drawbacks. They can be completed in a short time span and Chapuis et al. (1981) demonstrated that their interpretation does not necessitate the PL of the surrounding soil layer.

This paper will review the theoretical background for the interpretation of falling-head tests and present five (5) interpretation methods: log (or Hvorslev), velocity (or Chapuis), alternate velocity, Z-t and optimised log (or corrected Hvorslev). Each method will be applied on synthetic datasets. Data within each set includes a random error component of predefined variance. The object will be to evaluate how each interpretation method is sensitive to random measurement error. A comparison between methods and a discussion on the interpretation of falling-head tests will follow.

2 INTERPRETATION OF FALLING-HEAD TESTS

Data from falling-head tests, be they obtained in the laboratory or in the field, may be interpreted by a number of methods. Chapuis (1998) indicates that when the deformations of the soil can be neglected, falling-head tests are governed by the Laplace equation. Its solutions, the harmonic functions, have several properties. One of them relates flux into the soil (Q_{soil}) to flow into the pipe (Q_{inj}) through a mass-balance equation.

$$Q_{inj} = Q_{soil} = ckH \qquad [3]$$

where c is a shape factor that depends on the geometry of the injection zone and on the hydraulic boundaries of the problem, H is the applied hydraulic head difference and k is the hydraulic conductivity. This equation is the starting point of the Hvorslev, velocity (Chapuis) and Z-t methods. Another equation is the starting point of another method for cases where the soil deformation is assumed to be elastic and not negligible (Cooper et al. 1967). However this method contains physical and mathematical confusions according to the mathematical, physical and numerical proofs by Chapuis (1998), and the experimental proofs of Chapuis and Chenaf (2002). According to the equations of Chapuis (1998), the effect of soil deformation can be neglected when the soil is an aquifer or an overconsolidated aquitard. It is no longer negligible for compressible aquitards when they are tested using either a falling-head test with a very small injection pipe or a pulse test between packers. Chapuis and Cazaux (2002) gave suggestions on how to correctly handle the instantaneous (elastic) and delayed deformations in such cases. In a falling-head test, Q_{inj} is the flow through the inflow pipe (often a standpipe connected to the borehole casing) of internal cross-section S_{inj}.

$$Q_{inj} = -S_{inj}\frac{dH}{dt} \qquad [4]$$

where t is time. Eqs.[3] and [4] yield:

$$\frac{dH}{dt} = -\frac{c}{S_{inj}}kH \qquad [5]$$

Rearranging gives:

$$\frac{dH}{H} = -\frac{c}{S_{inj}}kdt \qquad [6]$$

Integrating leads to the solution proposed by Hvorslev (1951):

$$\ln\left(\frac{H_j}{H_{j+1}}\right) = -kC(t_j - t_{j+1}) \qquad [7]$$

where H_j is the head loss at time t_j obtained from the difference between the total head in the inlet standpipe and PL at the boundary of the surrounding soil, and $C=c/S_{inj}$ is a shape factor that depends on the inlet/outlet geometry (see Chiasson 2005 for recommended shape factor equations for field tests). In the case of laboratory falling-head tests, C is given by:

$$C = \frac{A}{aL} \qquad [8]$$

where A is the area of the permeameter cross-section, “a” is the cross-section of the inlet standpipe and L is the flow distance through the soil sample. In the laboratory, the outlet is a constant head basin controlled by an overflow weir. In the field, the outlet head is set by the boundary conditions of the surrounding soil, i.e. the PL of the surrounding soil. In the laboratory, it is relatively easy to accurately and precisely measure the outlet piezometric head. In the field, an accurate measure of the PL of the surrounding soil is not necessarily trivial. An error in measurement will introduce an error in head difference H_j of equation [7]. Chapuis (1999) and Chiasson (2005) showed that this error will produce a curved ln H versus time plot. Since the hydraulic conductivity k is the slope of this plot, a curved plot implies that k changes with time. A concave downward curve suggests that k increases during the duration of the test. If the test is repeated with the same error in the PL of the surrounding soil, the same result will be observed. Chiasson (2005) mathematically demonstrated that when the error in the PL of the surrounding soil is not zero (i.e. $H_o \neq 0$), the relationship between hydraulic conductivity and the slope of the plot as expressed by eq. [7] is no longer valid. Chiasson concluded that the direct use of equation [7] proposed by Hvorslev without questioning the PL value is not recommended. Chiasson (2007) furthermore concludes that Hvorslev’s equation is incomplete and proposes to replace this method by the corrected Hvorslev method (or optimized log) that is described later.

2.1 Velocity method

The velocity method proposed by Chapuis et al. (1981) is one where the unknown PL of the soil is not needed for hydraulic conductivity determination. Therefore, an error in the assumed PL has no consequence for computations. For this method, the following definition is first introduced:

$$H(t) = Z(t) + H_o \qquad [9]$$

where H_o is the distance between Z(t), the elevation above ground of the inlet falling water level within the standpipe and the PL of the surrounding soil (Figure 1). If Z(t) is erroneously assumed as the total head loss between inlet and the PL of the soil, H_o can be seen as a systematic error, or bias. Rearranging equation [5] using [9] then gives:

$$Z = -\frac{1}{Ck}\frac{dZ}{dt} - H_o = m_v\frac{dZ}{dt} - H_o \qquad [10]$$

By plotting y = Z as a function of x = v = dZ/dt, a straight line should be obtained with slope m_v=-1/Ck and intercept H_o. Thus, the slope of this plot is related to k by:

$$k = -\frac{1}{m_v C} \quad [11]$$

2.2 Alternate velocity method

The velocity method uses least square estimation to yield the best unbiased linear fit. Chiasson (2007) argued that statistical estimation by least squares is theoretically based on one dependant variable being a function of another that is independent. The independent variable is a controlled variable, i.e. it is the user that decides at which value a measurement of the dependant variable will be made. Thus, by definition, the independent variable has no measurement error.

In the velocity method, velocity v during a time increment Δt is considered as the independent variable and the average elevation Z_m [$(Z_j+Z_{j+1})/2$] during the time increment is the dependent variable. When data has low scatter in Z (or t), this has little effect on the result. When data has some scatter in Z (or t), Chiasson (2005, 2007) shows that interpretation problems arise! The act of choosing v as the controlled variable when it has high statistical scatter clearly departs from least square estimation theory.

Between variables v and Z_m, Z_m displays the least measurement error. One could thus choose to consider Z as the control variable and time t could be measured at a certain value of Z. With Z_m as the control variable, velocity $v = \Delta Z/\Delta t$ is the dependant variable. This makes more sense since by definition velocity v is a function of elevation Z and time t, i.e. it is dependant on Z and t. Rearranging equation [10]

] to obtain v on the left hand side gives:

$$v = \frac{dZ}{dt} = -CkZ - CkH_o = m_Z Z + b_Z \quad [12]$$

From equation [12], the hydraulic conductivity k and the bias H_o are:

$$k = -\frac{m_Z}{C} \quad [13]$$

and

$$H_o = \frac{b_Z}{m_z} \quad [14]$$

2.3 Z-t method

A third method proposed by Chiasson (2005) plots raw elevation data Z as a function of time t. The solution for equation [6] using [9] is as follows (see Chiasson, 2005 for demonstration):

$$Z = H_i e^{-at} - H_o \quad [15]$$

where H_i is the head difference at initial time $t_j=t_0=0$ and "a" is a parameter where:

$$k = \frac{a}{C} \quad [16]$$

Let Z_j be the measurement of Z at time t_j, for j={0, ... n}, and let $Z^*(t_j)$ be the estimated water level in the piezometer at time t_j, using estimated parameters H_i^*, a^* and H_o^*. The best unbiased estimator will then be obtained by numerically minimising the following equation:

$$\mathrm{MIN}\left(\sum_{j=0}^{n}\left[Z_j - Z^*(t_j)\right]^2\right)$$

while subjected to the unbiased condition:

$$\sum_{j=0}^{n}\left[Z_j - Z^*(t_j)\right] = 0$$

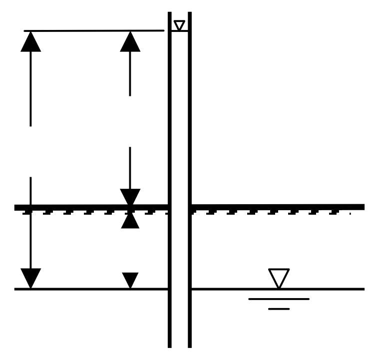

Figure 1. Setup for a falling-head test in an unconfined aquifer.

2.4 Corrected Hvorslev's method or optimised log [Z+H$_o$] method

In Hvorslev's original interpretation method, $\log(H_j/H_i)$ is plotted as a function of time t. In doing this, Hvorslev made two implicit suppositions: that H_o is a priori known and that the initial reading for H_i at time $t_0 = 0$ has no measurement error. Clearly, this is rarely the case. Chapuis (1999) and Chiasson (2005) show how making these implicit suppositions will adversely affect the interpretation of the test and the value of the hydraulic conductivity k. Chapuis proposes to use the velocity method to obtain H_o and interpret the falling-head test by rearranging equation [7] using eq. [9] to obtain;

$$\ln(Z_j + H_o) = -kCt_j + \ln(Z_0 + H_o) \quad [17]$$

and to plot $y = \ln(Z_j+H_o)$ in function of $x = t$. Unfortunately, this approach is incomplete since it needs to implicitly make the supposition that the initial reading at time $t_0 = 0$

has no measurement error. Since the error on the first reading Z_0 is usually small, the initial solution H_i of eq. [15] is practically equal to Z_0+H_o. Thus, the hydraulic conductivity will generally not be adversely affected. The hydraulic conductivity found this way is always close to being equal to the value obtained by the velocity method. From this, Chapuis (1999) concludes that this confirms the validity of the hydraulic conductivity value. Chiasson (2005) shows that if H_o and H_i are obtained by another interpretation method, i.e. the Z-t method, interpretation of a falling-head test using eq. [17] will give values equal to those obtained by the Z-t method! This brings Chiasson to conclude that eq. [17] (Hvorslev's method) with H_o estimated from another method (velocity or Z-t) cannot be used to confirm the validity of the k value obtained by the same other method (velocity or Z-t), since the value of k that is obtained is dependant of the method used to estimate H_o.

A remedy to this is to estimate H_o, H_i and k by a least square optimisation technique similar to the one used in the Z-t method. Rewriting eq. [17] with $H_i = Z_0 + H_o$, $m_{ln} = -kC$ and $b_{ln} = \ln(H_i)$ gives:

$$\ln\left(Z_j + H_o\right) = m_{ln} t_j + b_{ln} \qquad [18]$$

Let then $y^* = \ln(Z^*(t_j) + H_o)$ be the estimated natural logarithm of the total head in the piezometer at time t_j, with estimated parameters $b^*_{ln} = \ln(H_i^*)$, $m^*_{ln} = -k^*C$ and H_o^*. The best unbiased estimator will then be obtained by numerically minimising the following equation:

$$\mathrm{Min}\left(\sum_{j=0}^{n}\left[y_j - y^*(t_j)\right]^2\right)$$

while subjected to the unbiased condition

$$\sum_{j=0}^{n}\left[y_j - y^*(t_j)\right] = 0$$

This variant of Hvorslev's log method independently estimates all unknown parameters. Theoretically, it can be used to separately evaluate k and confirm values estimated by both velocity and Z-t methods.

3 INTERPRETATION METHODS AND THEIR STATISTICAL ROBUSTNESS

The solution for differential equation [6] expressed by eq. [15] with $H_i = 701$ mm, $H_o = 400$ mm and $k = 5 \times 10^{-7}$ mm/s and a test setup giving a shape factor $C = 235.3$ mm^{-1} was used to generate synthetic data as follows:

$$\mathbf{Z} = \left[(701\ \mathrm{mm})e^{-1.176\times10^{-4}t} - 400\ \mathrm{mm}\right] + \varepsilon \qquad [19]$$

where ε is a normal law distributed random fluctuation with zero mean and standard deviation $\sigma = \Delta Z/1.96$. The random fluctuation component corresponds to a synthetic random measurement error. By definition, ΔZ is the absolute error of the synthetic dataset of measurements Z. Six synthetic datasets of increasing absolute error on Z were generated this way. Absolute errors for each synthetic dataset will be in increasing order ΔZ =: ±0.10 mm, ±0.25 mm, ±0.50 mm, ±0.75 mm, ±1,0 mm and ±2.0 mm. Each absolute error dataset is composed of 40 synthetic tests with each test composed of 18 synthetic measurements spanning from t = 0 to 2040 seconds.

Each method reviewed earlier is applied to these six synthetic datasets to investigate their sensitivity to data affected with random measurement error.

3.1 Velocity method

As underlined earlier, when measurement errors on Z are small, the velocity method will yield good results! An illustration of this statement is given in Figure 2. In this plot, the measurement error on Z is only of ± 0.10 mm. Using $m_v = -8422.3$ sec^{-1} from Figure 2, $C = 235.3$ mm^{-1} and eq. [11], one finds $k = 5.05 \times 10^{-7}$ mm/s and Ho = 394.5 mm. Both hydraulic conductivity k and bias H_o are by all practical means equal to the no-error-imposed solution of $H_o = 400$ mm and $k = 5 \times 10^{-7}$ mm/s. This gives a relative error of only 0.92% for k and 1.4% for H_o.

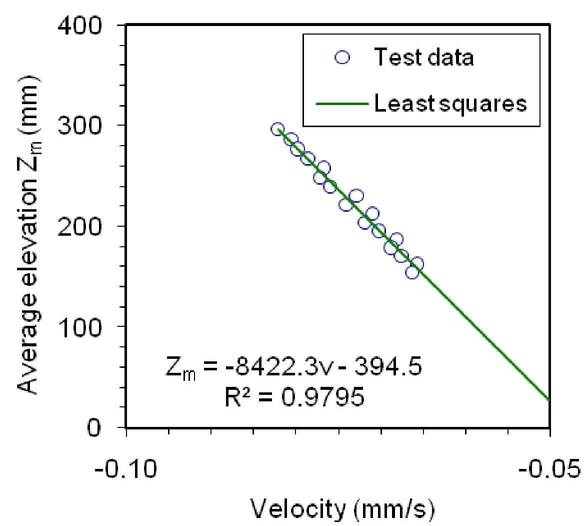

Figure 2. Velocity plot of synthetic test data (ΔZ = ± 0.10 mm).

When measurement errors on Z are relatively high (in the order of 0.3 to 0.6%), the velocity plot displays considerable scatter (Figure 3). Such a plot will also suggest that data from such a test is of questionable quality. Using the same shape factor and equation, one finds $k = 1.61 \times 10^{-6}$ mm/s and $H_o = -28.8$ mm, giving a 222% relative error for k and -107% relative error for H_o. Hence, relatively small measurement errors in elevation Z (i.e. 0.3 to 0.6%) yield very high estimation error in k and H_o.

Chiasson (2007) observes that the velocity method systematically gives higher k values than the methods earlier presented. The six synthetic datasets, generated by eq. [19] with ΔZ: ±0.10 mm, ±0.25 mm, ±0.50 mm, ±0.75 mm, ±1,0 mm and ±2.0 mm, confirm this systematic bias (Figure 4). Also, as measurement errors increase on elevation of falling-head, the velocity method yields on average a higher hydraulic conductivity.

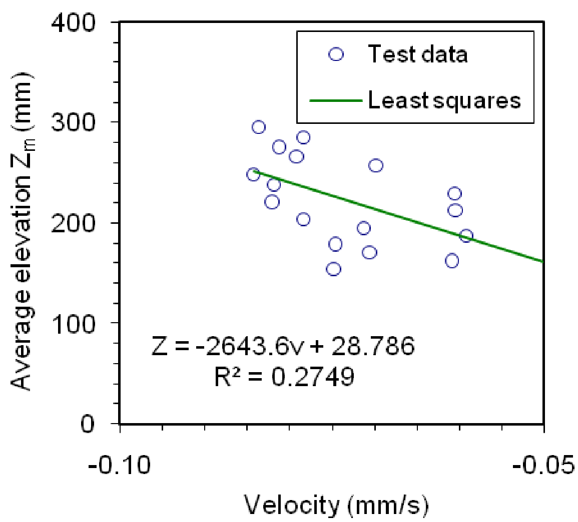

Figure 3. Velocity plot of synthetic test data (δ_Z = 1.0 mm).

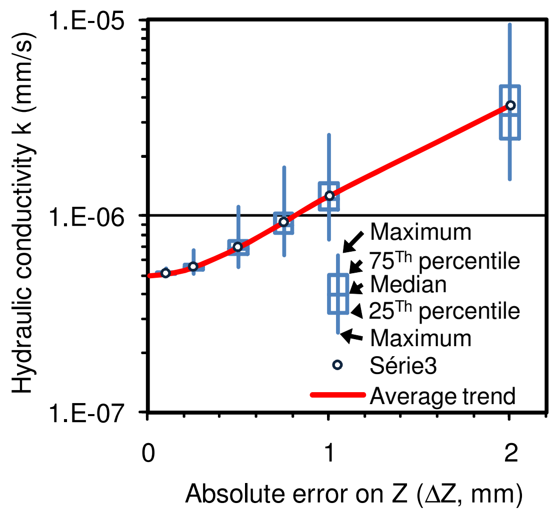

Figure 4. Scatter of hydraulic conductivity computed from velocity method as a function of absolute error of synthetic dataset formed of data couples of falling water column elevations Z and times t.

There is a clear correlation between measurement error on Z and hydraulic conductivity obtained from the velocity method (Figure 4). Furthermore, a good correlation is observed between the absolute error on k obtained by the velocity method and the coefficient of determination of the plot (Figure 5). This further demonstrates that the velocity method is not statistically robust. This method should not be used when data scatter is observed in the velocity plot, i.e. when R^2 is less than 0.92. Thus, when coefficients of determination will be higher than this threshold, relative error on k will be below 10% (Figure 5).

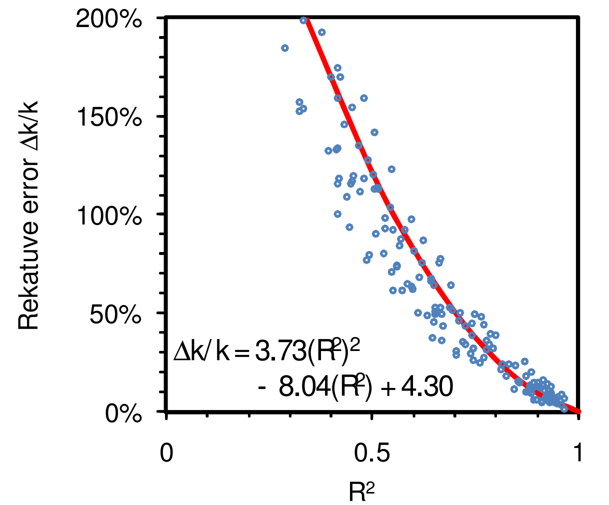

Figure 5. Relative error on hydraulic conductivity k in function of coefficient of determination R^2 obtained from velocity method plots.

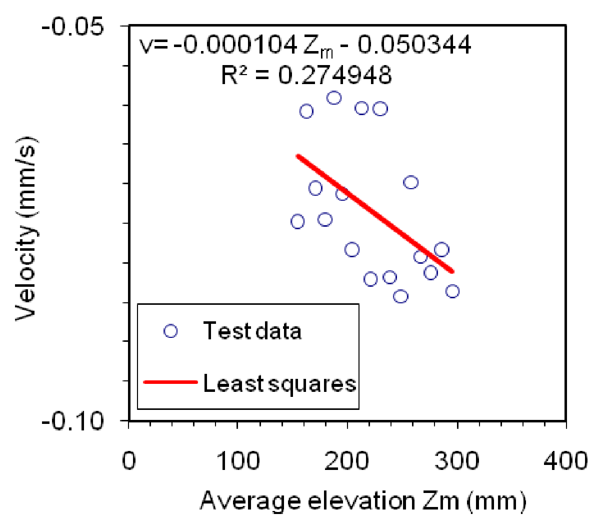

Figure 6. Alternate velocity plot for data of Figure 3 (synthetic test data with δ_Z = 1.0 mm).

3.2 Alternate velocity method

The alternate velocity method, being developed on a sounder theoretical basis, should be more statistically robust, i.e. less sensitive to data scatter. The same data that was plotted in Figure 3 is used to illustrate this hypothesis. The alternate plot of velocity v in function of average elevation of falling-head Z_m does not yield a better correlation coefficient, the scatter being the same (Figure 6). The hydraulic conductivity computed from this plot is on the other hand quite different. Using eq. [13], the same shape factor C and slope m_Z from Figure 6 yields k = 4.42 x 10^{-7} mm/s and H_o = 484 mm. With the alternate plot, relative error for k has decreased to -11.6% and to 21.0% for relative error on H_o. This is a considerable improvement in relation to the 222% relative error for k and -107% relative error for H_o that was obtained earlier with the velocity method. Computed hydraulic conductivity values from alternate velocity method show no correlation with test data scatter as characterised by the coefficient of determination (Figure 7).

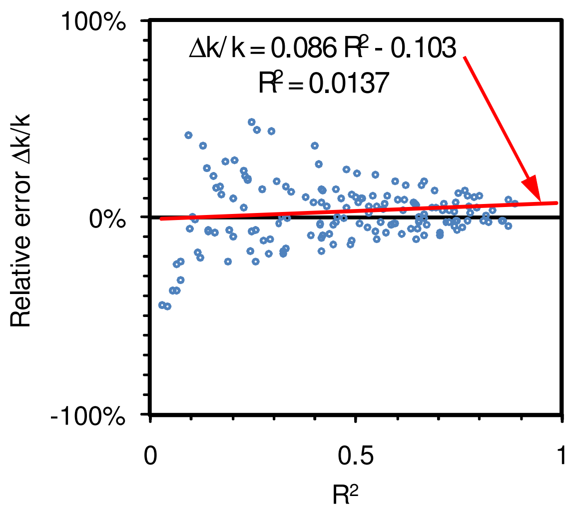

Figure 7. Relative error on hydraulic conductivity k in function of coefficient of determination R^2 obtained from alternate velocity method plots.

On average, the alternate velocity method will yield good hydraulic conductivity values but data scatter, although less problematic than for the velocity method, still yields rather high relative errors for k. The alternate velocity method can thus be qualified as being relatively unbiased, thus on average accurate but not precise. Results from this study indicate that the alternate method should be used with caution when data scatter for the alternate velocity plot yields R^2 less than 0.87. Otherwise, the relative error for k may be greater than ±10% (Figure 7).

3.3 Z-t method

Chiasson (2005) introduced this method after observing that scatter in the velocity plot (likewise with the alternate velocity plot) is inherent to the computation of the velocity. Chiasson thus proposes to use raw data, i.e. [t_j, Z_j] data couples, and directly plot them on a Z-t graph. Difference in scatter is evident when comparing scatter in the velocity plot (or alternate velocity) with scatter in the Z-t plot (compare Figure 3 and Figure 6 with Figure 8).

Applying the Z-t method to the same dataset earlier used with velocity and alternate velocity methods gives k = 4.68 x 10^{-7} mm/s, H_o = 439.5 mm and H_i = 739.9 mm. This corresponds to a relative error for k of -6.4% and of 9.9% for relative error on H_o. This is an improvement comparatively to earlier presented methods, velocity or alternate velocity.

The Z-t method is unbiased; i.e there is no significant correlation with scatter intensity (Figure 9). It yielded high coefficients of determination for the complete suite of studied absolute errors, meaning that equation [15] well explains the relationship.

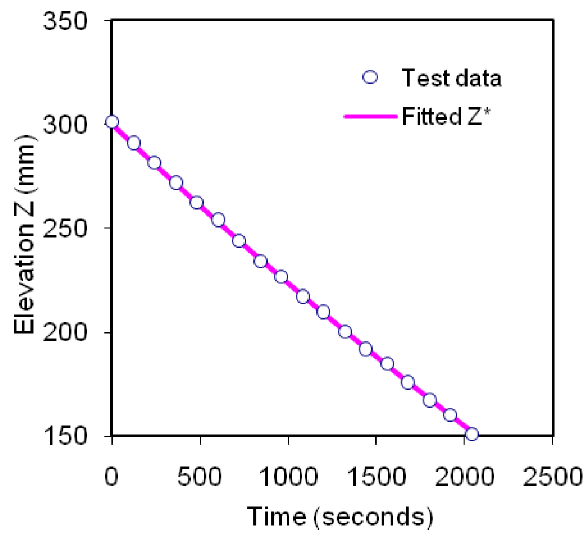

Figure 8. Z-t plot for data of Figure 3 (synthetic test data with δ_Z = 1.0 mm).

The Z-t method yields good hydraulic conductivity values and it is less sensitive to data scatter (Figure 9 and Figure 10). The Z-t method is thus an accurate interpretation method. It is also a precise method since relative error on k is of only 3.6% when synthetic data has ΔZ = 0.25 mm and increases by approximately the same amount for each 0.25 mm increment to ΔZ. Results from this study indicate that the Z-t method can be used even when absolute error on Z is of the order of 2.0 mm ($\Delta Z/Z$ = 1.3%) for which relative error on k will be of 28.4%.

3.4 Corrected Hvorslev's method or optimised log [Z+H_o] method

Again, for the same dataset used for the other three methods, the corrected Hvorslev method gives k = 4.40 x 10^{-7} mm/s, H_o = 482.6 mm and H_i = 783.1 mm. This result for k is approximately equivalent in accuracy to the Z-t value obtained earlier. Investigating the complete dataset of synthetic data, results for k show some sensitivity to data scatter, more than in the case of the Z-t method (Figure 11). The method thus appears acceptable when $\Delta Z < 1.0$ mm. Higher absolute errors in Z appear to destabilise the method. This may be due to numerical optimisation which is less stable for this method.

4 CONCLUSION

Interpretation methods for falling-head tests were evaluated for their sensitivity to measurement error in elevations measurements of the falling water column. The velocity method is found to be the less appropriate one for computing hydraulic conductivity, even when measurement errors are relatively small. It tends to systematically overestimate the true hydraulic conductivityThe introduction of an error on Z will always have a greater impact on v than on Z_m,, (Chiasson 2005 and 2007), thereby always increasing the scatter range of v values more than the scatter range of Z_m values. As a consequence, the slope of the velocity graph will flatten, lowering the slope and thus yielding a higner estimated k.

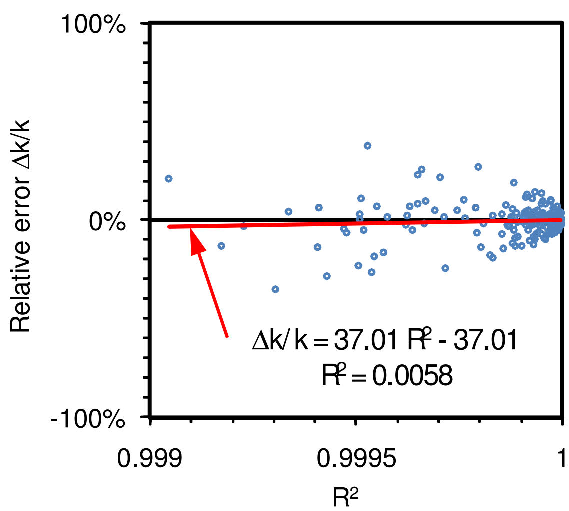

Figure 9. Relative error on hydraulic conductivity k in function of coefficient of determination R^2 obtained from Z-t method.

An easy corrective measure is to plot the alternate velocity method. This method, which is just a permutation between independent and dependent variables used in the velocity plot, is found to be accurate (i.e., on average, it yields the correct k). The alternate velocity method also displays considerably less scatter in computed k values. It is thus recommended to replace the classical velocity plot by the more statistically robust alternate velocity method.

The best method is found to be Z-t, with the corrected Hvorslev trailing not too far behind. Both these methods are accurate and the Z-t is particularly precise when compared to the other studied methods.

By using more than one method, it is possible to better evaluate the accurateness and precision of computed hydraulic conductivity. As a rule of thumb, if the difference between the alternate velocity plot and the Z-t method is small, the Z-t value can be considered as accurate and precise. If absolute errors on Z are less than ±1.0 mm, this study shows that it may be concluded that computed hydraulic conductivity values are accurate and precise.

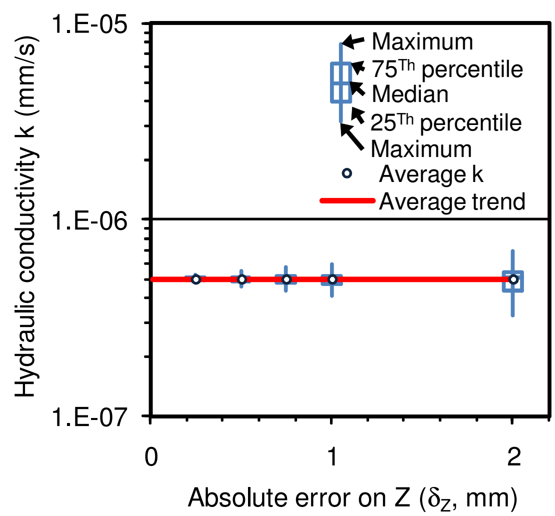

Figure 10. Scatter of hydraulic conductivity computed from Z-t method in function of absolute error of synthetic elevations.

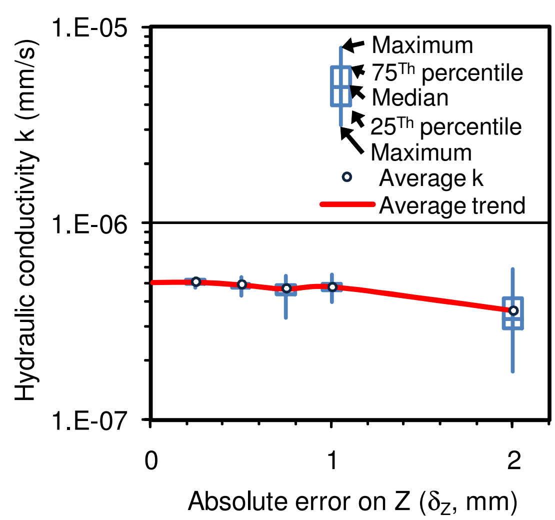

Figure 11. Scatter of hydraulic conductivity computed from corrected Hvorslev method in function of absolute error of synthetic elevations.

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