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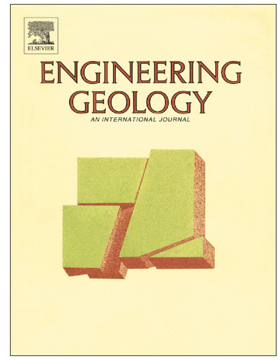

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by

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Abstract

This paper quantifies the influence of seasonal hydraulic head changes in shallow low-permeability soils on the hydraulic conductivity (*K*) values obtained from slug tests. A total of 61 slug tests with durations between 3 and 6 weeks were conducted between 2007 and 2010 in 17 monitoring wells (MWs) installed in a clay deposit in Lachenaie, Canada. Beginning in 2012, vibrating wire piezometers (VWPs) were sealed in some of the MWs to record the seasonal hydraulic head cycles. To get a better understanding of the influence of seasonal head changes on the variability of *K* measurements for the Lachenaie tests sites, a series of 936 slug tests were modelled using COMSOL. The seasonal head changes measured with the VWPs were applied as a boundary condition 2 m away from the MW intake zone. Different types of slug test (rising- or falling-head) were launched at different times of the year. The velocity graph method, a graph of the apparent hydraulic head in the MW versus its rate of change, was used to interpret both the experimental and numerical slug test data. Both the experimental and numerical results show that seasonal head changes have a systematic influence upon the middle part of the velocity graph, the part used to calculate *K*. This influence depends on time of year, type of test (rising- or falling-head), initial hydraulic head difference and clay properties. In Lachenaie, the influence of seasonal hydraulic head changes on *K* is shown to be at least of the same order (factor 1.1) as the influence of clay deformation.

Keywords: clay, monitoring well, slug test, natural hydraulic head cycles, velocity graph

1. Introduction

The Lachenaie experimental test sites were designed to study the pore water geochemistry and geotechnical properties of the local Champlain clay deposit. Since 2007, 61 variable-head permeability tests with a riser piper diameter (d) of 52.5 mm have been conducted in 17 monitoring wells (MWs) installed in the Lachenaie clay deposit.

The main motivation behind the field permeability test campaign was to obtain the hydraulic conductivity values (K) needed to calculate ground water velocities and the advective component of solute transport in the clay deposit. In situ measurements of K are often stipulated in the environmental bylaws and regulations of legislative bodies. For example, in Quebec, the clay K value must be measured in situ if one plans to use the soil to contain landfill leachate (MDDEP, 2005).

In situ permeability tests in general are known to be affected by a wealth of errors that can be caused, for example, by faulty monitoring well installations (e.g., Chapuis and Sabourin, 1989) or ill-advised testing methodologies (e.g., Bjerrum et al., 1972). Tests performed in clay tend to be affected by specific problems. One major difficulty with tests in low-permeability materials is their long duration. In Lachenaie, when using the 52.5-mm riser pipe, slug tests can last up to 8 weeks. During this period, the background hydraulic head in the low-permeability soil can be modified by seasonal head changes that may reach and exceed 1.0 m. Smaller riser pipes or pulse tests can be used to circumvent the long test duration. For example, in Lachenaie, pulse tests conducted by installing a packer into the 52.5-mm riser pipe last less than two hours. On the other hand, these shorter tests tend to magnify the importance of the transient flow, which feeds pore volume change in the clay, with respect to the steady state flow component used to calculate K (Bredehoeft and Papadopulos, 1980; Duhaime and Chapuis, 2014).

The influence of seasonal head changes on long-duration permeability tests was studied numerically by Chapuis et al. (2012) using one example with realistic clay properties and monitoring well geometry. They based their analysis on the velocity graph method (Chapuis et al., 1981), a simple procedure that allows the Hvorslev (1951) family of interpretation methods to be used when the piezometric level in a MW is not known a priori. Their results have shown that numerical velocity graphs in soft clay deposits can have three distinct parts. The first part is curved because of clay deformation. The second part is straight and should be used to interpret the test data. The third part also shows a curvature, but due to seasonal hydraulic head changes.

The main objective of this paper is to evaluate the influence of seasonal head changes on real slug tests using the Lachenaie dataset and numerical slug test results based on the seasonal head cycles recorded in Lachenaie with vibrating wire piezometers (VWPs) (Marefat et al., 2015). The paper first introduces the methodology for the field tests, the hydraulic head monitoring and the numerical slug tests. A comparison of the experimental and numerical results regarding the influence of seasonal head variations on slug tests follows.

To the authors' best knowledge, this paper is the first to appraise the impact of seasonal hydraulic head cycles on *K* based on both large experimental datasets for slug tests and long-term hydraulic head measurements, and systematic numerical simulations based on real hydraulic head cycles. The paper clearly demonstrates that a significant part of the variability of in-situ *K* measurements for the Lachenaie experimental test sites can be explained by the influence of seasonal head changes, and that this variability is significant when compared to the influence of clay deformation. The experimental and numerical results also show that the testing methodology, especially the initial hydraulic head and the type of test (falling- or rising-head tests), has an influence on the *K* error due to hydraulic head cycles.

2. Methodology

2.1. Slug tests and hydraulic head measurements for the Lachenaie test sites

The Lachenaie test sites are spread over a 50 km^2 area north of the Mille-Îles River, near Montreal, Canada (Fig. 1). The 17 MWs are concentrated on 9 sites. The stratigraphy encountered on each site is similar (Fig. 2). The unoxidised Champlain clay layer in which the MW intake zones are installed has a thickness varying between 10 and 25 m.

Up to 5 m of sand or oxidised clay can be present locally on top of the massive clay layer. The clay is underlain by up to 7 m of till and the fractured Palaeozoic shale bedrock.

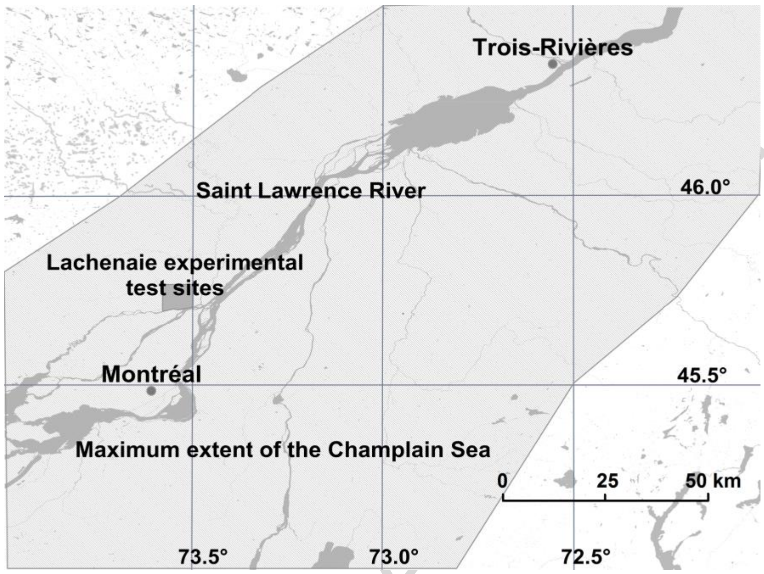


Fig. 1. Location of the Lachenaie experimental test sites within the Champlain Sea basin (adapted from Duhaime and Chapuis 2014).

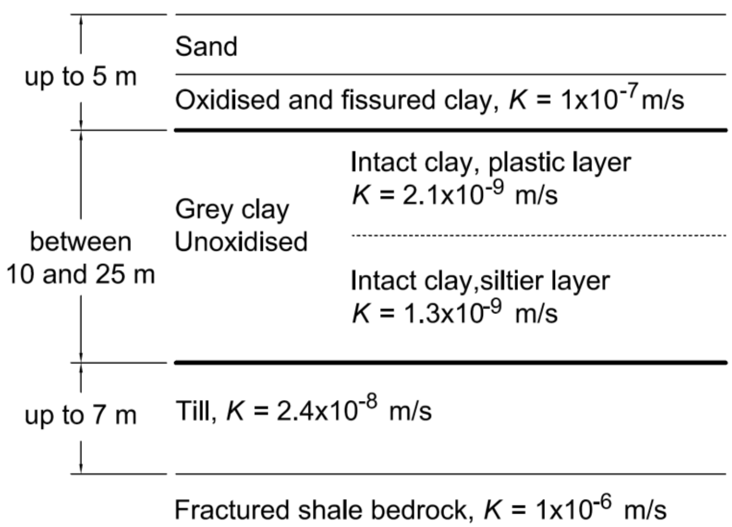


Fig. 2. Simplified stratigraphy and hydraulic conductivity for the Lachenaie test sites.

The unoxidised clay layer comprises two sublayers (Fig. 2) which differ by their percentage of clay-size particles (CF, particle size < 2 µm) and their liquid limit (w_L). The top layer is finer and more plastic (w_L > 60%, CF > 65 %), while the lower layer is siltier (w_L < 60%, CF < 65 %). The intake zones of eight MWs are located in the top layer, seven are installed in the bottom layer and two straddle the boundary between the two layers.

The clay is overconsolidated. The undrained shear strength and preconsolidation pressure of the intact clay can reach 100 kPa and 580 kPa respectively. These values are relatively high for Champlain clay. The upper and lower clay sublayers produced similar K values during the field and laboratory testing programs described by Duhaime et al. (2013). A mean K value of approximately 2×10^{-9} m/s was obtained. Falling-head permeability tests conducted in oedometer cells on vertical and horizontal intact specimens showed K to be nearly isotropic. The mean ratio of horizontal (K_h) and vertical (K_v) hydraulic conductivity values obtained for 10 pairs of tests was $K_h/K_v = 1.2$ (Duhaime, 2012). This low value is consistent with the relatively high void ratio and water content of Champlain clays (Chapuis and Gill, 1989; Leroueil et al., 1990).

On all sites but one, two MWs were installed at the upper and lower thirds of the clay layer. A detailed description of their installation was presented by Duhaime (2012) and Duhaime and Chapuis (2014). A schematic representation is shown in Fig. 3a. The MWs riser pipe has an inside diameter d = 52.5 mm. Their intake zone is filled with a fine sand filter. On top of each intake zone, bentonite pellets and cement-bentonite grout were used to seal the annular space around the riser pipe. Intake zone length varies slightly for each MW. Their mean diameter and length are respectively D = 83.5 and L = 1002 mm.

Between 2007 and 2010, a total of 61 slug tests were conducted in the 17 MWs. Variable-head tests were initiated by rapidly changing the water level in the MW riser pipes. Initial water level changes $H(t=0)$ of between -2 m (rising head) and 2 m (falling head) were used. Where it was allowed by the initial static water level, four tests were conducted in each MW with $H(t=0)$ of -2, -1, 1 and 2 m. In some cases, the static water level was too close to the top of the riser pipe to conduct a falling-head test with an initial head of 2 m.

In some other cases, the water level was too close to the screen to conduct a rising-head test with $H(t=0) = -2$ m without lowering the water level to the screen.

Beginning in 2012, VWPs were grouted in 10 of the project MWs to measure seasonal hydraulic head cycles without the influence of the long time lag associated with riser pipes with $d = 52.5$ mm. Each VWP was installed in a sand filter within the pre-existing MW riser pipe. The MWs were sealed with bentonite pellets and cement-bentonite grout. Since then, pore pressure and barometric pressure measurements have been recorded every 15 minutes. A detailed description of the VWPs installation and pore pressure correction from barometric pressure effects was presented by Marefat et al. (2015).

Two types of interpretation methods are used to calculate K from slug test data. They both assume that Darcy's law is valid and they use the same water conservation equation (Richards 1931):

$$K\nabla^2 h = \frac{\partial \theta}{\partial t} \quad (1a)$$

in which the second term is either assumed negligible (Hvorslev 1951), or simplified as:

$$\nabla^2 h = \frac{S_s}{K}\frac{\partial h}{\partial t} \quad (1b)$$

In Eq. 1, h is the hydraulic head field in the soil, t is the time variable and S_s is the specific storage, a parameter describing the soil skeleton and water compressibility. The ratio K/S_s is equivalent to the Terzaghi consolidation coefficient (c_v). Equation 1b is obtained after assuming a homogeneous, isotropic and saturated material, constant total stress and a linear relationship between water pressure and soil skeleton volume. Relationships 1a and 1b could also be non-linear. For example, Pudasaini (2016) presented an analytically derived sub-diffusion model that could better describe the fluid flow in porous media with quadratic diffusion flux. This model extends Darcy's law, is physically more suitable and has several advantages over the classical linear diffusion flux model as the mechanism of diffusion process in background fluid, and porous media are fundamentally different.

The interpretation methods of the Cooper et al. (1967) type are based on solutions to Eq. 1b (Butler, 1998), whereas methods of the Hvorslev (1951) type are based on the hypothesis of a negligible volumetric strain, which for the other theory corresponds to a perfectly rigid soil skeleton. This paper uses Eq. 1a to simulate the slug tests, but only the second type of interpretation methods where the right-hand side of Eq. 1a is assumed negligible.

Methods of the Hvorslev type are derived from an application of the water conservation principle at the interface between the soil and the sand filter. The flow of water entering the soil (Q_{soil} in Eq. 2) must balance the rate of change of the water volume stored in the riser pipe (Q_{pipe} in Eq. 3):

$$Q_{soil} = cKH \tag{2}$$

$$Q_{pipe} = -S_{inj}\frac{dH}{dt} \tag{3}$$

In Eqs. 2 and 3, H is the difference between the hydraulic head in the riser pipe and the background hydraulic head in the soil, S_{inj} is the inner section of the riser pipe ($S_{inj} = \pi d^2/4$) and c is a shape factor calculated from the intake zone geometry (L and D) and the geometry of the tested layer (Hvorslev 1951).

The most common definitions for c come from analytical solutions to Laplace's equation ($\nabla^2 h = 0$) for idealized intake zone geometries. The ellipsoid formula presented by Hvorslev (1951) comes from the solution to Laplace's equation around a spheroid intake zone with a focal length of L in an infinite domain. Shape factor calculations for cylindrical intake zones using the finite element method (e.g., Duhaime and Chapuis, 2009; Ratnam et al., 2001) and semi-analytical solutions (e.g., Silvestri et al., 2012) show that the original ellipsoid formula gives c values that are slightly but systematically underestimated. Duhaime and Chapuis (2009) proposed the following modified version of the ellipsoid to correct this bias:

$$c = \frac{2.2\pi L}{\ln\left(\frac{L}{D} + \sqrt{1 + \left(\frac{L}{D}\right)^2}\right)} \tag{4}$$

Interpretation methods of the Hvorslev type integrate Eqs. 2-3 with respect to time. The following linear relationship between ln(H(t=0)/H) and t is then obtained:

$$\ln\left(\frac{H(t=0)}{H}\right) = \frac{cK}{S_{inj}} t \tag{5}$$

With Eq. 5, the slope of the linear relationship between ln(H(t=0)/H) and t is used to calculate K.

Other methods of the Hvorslev type are based directly on the differential form of Eqs. 2 and 3. This is the case for the velocity graph method (Chapuis et al., 1981). With this method, the time derivative of H, the water level velocity, is replaced by a finite difference approximation:

$$H_m = H_0 - \frac{S_{inj}}{cK} \frac{\Delta H}{\Delta t} \tag{6}$$

where H_m stands for the mean of H_i and H_{i+1}, the apparent head values used to calculate the velocity numerator ($\Delta H = H_{i+1} - H_i$) for time interval $\Delta t = t_{i+1} - t_i$. From Eq. 6, it can be seen that a plot of H_m versus the rate of change of the hydraulic head in the MW riser pipe ($\Delta H/\Delta t$, units of m/s) should produce a straight line for solutions of the Hvorslev (1951) type. On the other hand, solutions of the Cooper et al. (1967) type produce a smooth curve (Chapuis 2015). The slope of this straight line (S_{inj}/cK) allows K to be calculated (also units of m/s). The intercept H_0 is the piezometric error, a term added to Eq. 6 to acknowledge that the real head difference between the soil and the MW is not known a priori, especially for wells installed in shallow clay deposits. In low permeability materials, the MW water level is always lagging behind the soil hydraulic head (Chapuis, 2009; Chapuis et al., 2012).

In this paper, all slug tests were interpreted based on the velocity graph method. For comparison purposes, some numerical slug tests were also interpreted based on Eq. 5 to appraise the impact on the K value of assuming a background head equal to the initial static water level.

2.2. Numerical modelling of slug tests in a clay deposit with seasonal head changes

COMSOL's subsurface flow module and MATLAB programming interface were used to model a series of slug tests influenced by a cyclic boundary condition representing seasonal head changes. Equation 1b was solved over the 2-D axisymmetric domain shown in Fig. 3.

Two sets of K and S_s values were used in the simulations ($K = 2\times10^{-9}$ and 5×10^{-10} m/s, and $S_s = 2\times10^{-4}$ and 8×10^{-4} m^{-1}). These K values correspond respectively to the mean value in Lachenaie and an approximate lower bound to the measured values. This lower bound corresponds to longer tests that are more inclined to be influenced by seasonal head changes. The lower S_s value was deemed representative of the mean clay skeleton rigidity in Lachenaie based on pulse tests (Duhaime and Chapuis 2014). The other S_s value was used as an upper bound on the influence of clay compressibility during permeability tests.

The mean length and diameter for the filter sand pack of the Lachenaie MWs were used (L = 1002 mm and D = 83.5 mm). The model has a height of 5.00 m and a radius of 2.04 m. The mesh contains 27,933 triangular elements. Small elements (1 mm) were used at the interface between the sand filter and the intake zone. A detailed account of a parametric study that was conducted to obtain mesh-independent results for similar slug tests was presented in Duhaime (2012).

Apart from the impermeable or symmetry boundaries above and below the intake zone, two types of boundary conditions were applied on the domain boundaries. The first type of boundary condition verifies the conservation of water between the soil and the riser pipe (blue boundary on Fig. 3). It corresponds to Eq. 3. The second type of boundary condition is the cyclic hydraulic head profile that was applied at the distant boundary (red boundary on Fig. 3). The hydraulic head cycle was obtained by calculating daily mean values of the hydraulic head corrected for barometric pressure effects for two of the Lachenaie VWPs. These daily values were interpolated using cubic splines.

For each MW, more than two years of hydraulic head data were used. A period of at least 386 days allowed the model to reach a cyclic state with respect to the hydraulic head boundary condition. After this initial period, the model was stopped at 2-week intervals. Six slug tests were started at each stoppage point (falling- and rising-head tests with water level changes of 0.5, 1 or 2 m). Each test lasted 2 months. The cyclic boundary condition for hydraulic head was maintained during each test.

For each test, the middle third of the test data was selected to determine a straight line (between H_m = 0.33H(t=0) and 0.67H(t=0)). The slope and intercept of these straight lines were used to calculate K and H_0. Equation 5 was also used to calculate K. As it is customary with Eq. 5, all data were used to determine the linear trend, not just that of the middle third.

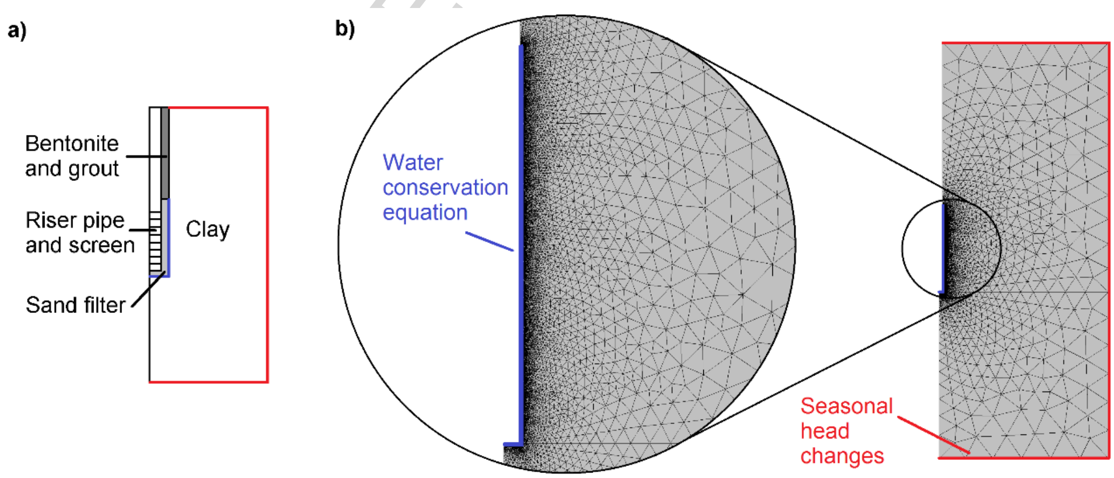


Fig. 3. Schematic representation of a MW (a) and corresponding mesh and boundary conditions for the slug test model in COMSOL (b).

3. Results and discussion

3.1. Seasonal hydraulic head cycles

Figure 4 shows the hydraulic head time series that were obtained with the VWPs installed in the MWs of sites 2 and 6. Site 2 is located on a flat terrain, while site 6 is located at the crest of a slope. For each MW, the difference between the hydraulic head on a given date and its mean value since installation is plotted. Raw hydraulic head data were corrected for the influence of barometric pressure changes using loading efficiency values (ratios between changes in pore pressure and barometric pressure) of respectively 0.92 and 0.80 for the upper and lower MWs of site 2, and 0.77 and 0.50 for the upper and lower MWs of site 6 (Marefat et al., 2015).

Even if the hydraulic head cycle amplitude varies from one site to another and at different depths within the clay layer, the frequency and general aspect of the hydraulic head cycles are similar for most VWP records. These typical hydraulic head cycles are exemplified on Fig. 4 by the record for both MWs of site 2 and the lower MW of site 6. For these records, the hydraulic head reaches a maximum value after snow melt at the beginning of summer (April to June). It then decreases during the warmer months of summer until October when it starts increasing again (Fig. 4). For some wells, such as the upper MW of site 2, the hydraulic profile reaches a plateau during spring and summer. This observation is consistent with the piezometric data presented by Kenney and Lau (1984) and Urciuoli et al. (2016) for other shallow clay deposits.

Shallow wells that are installed near or into the oxidised crust (Fig. 2) tend to show sharper, more erratic hydraulic head changes. This type of profile is exemplified by the piezometric record for the upper MW of site 6 on Fig. 4b. Its most striking feature is the rapid hydraulic head increase observed each year at the beginning of April. This rapid increase is associated with soil thawing, precipitation, a rapid increase in air temperature, and the spring high flood in the nearby river. The latter strongly modifies the hydraulic heads within the fractured rock aquifer than underlies the clay deposit, and thus the clay deep boundary hydraulic condition. A similar increase in hydraulic head during thawing has been observed elsewhere in the Champlain Sea basin (Demers et al. 2009).

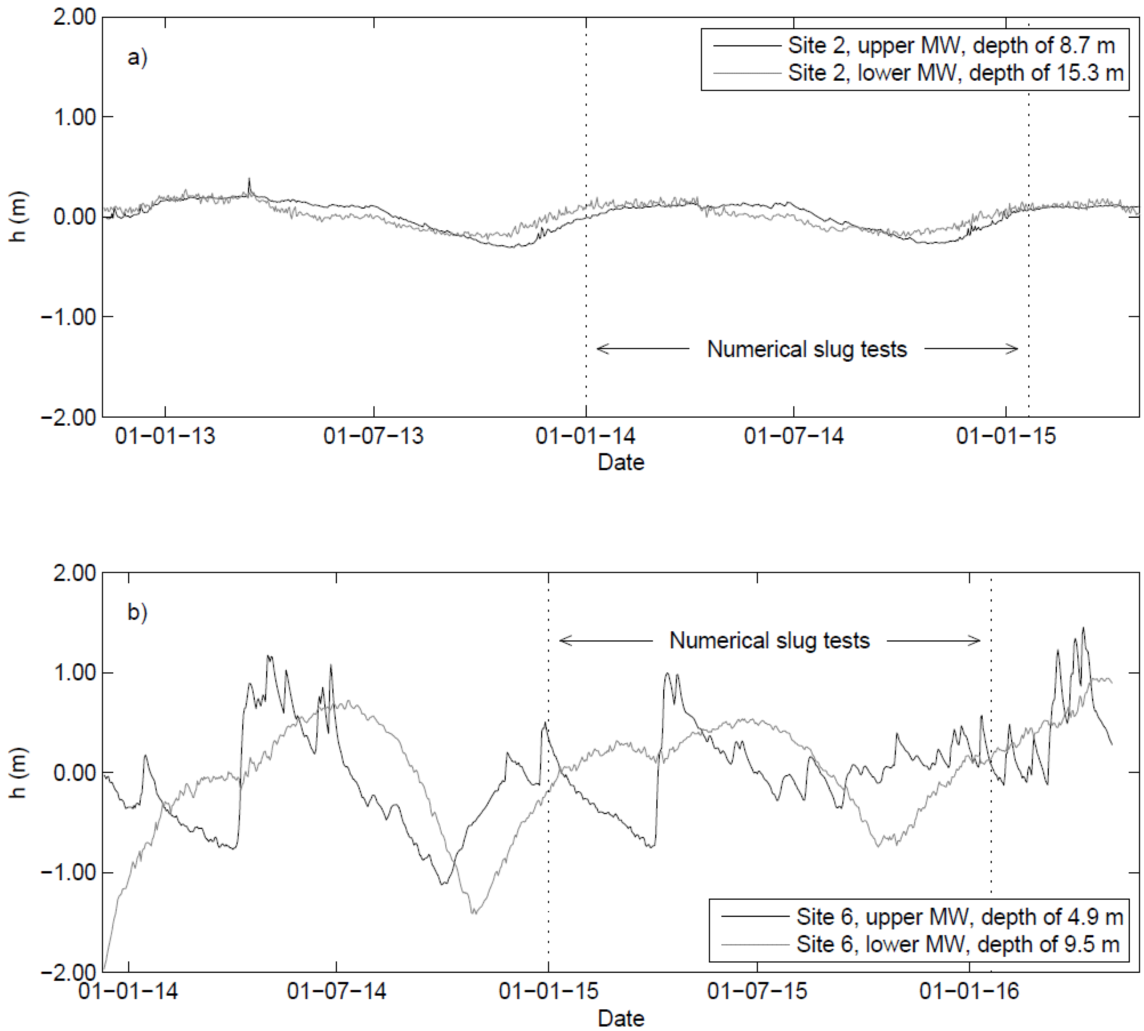


Fig. 4. Seasonal hydraulic head variations as measured with vibrating wire piezometers in the clay layer on a) site 2 and b) site 6. The hydraulic head values represent daily mean values corrected for barometric pressure variations. They are expressed relative to the mean hydraulic head measured for each piezometer.

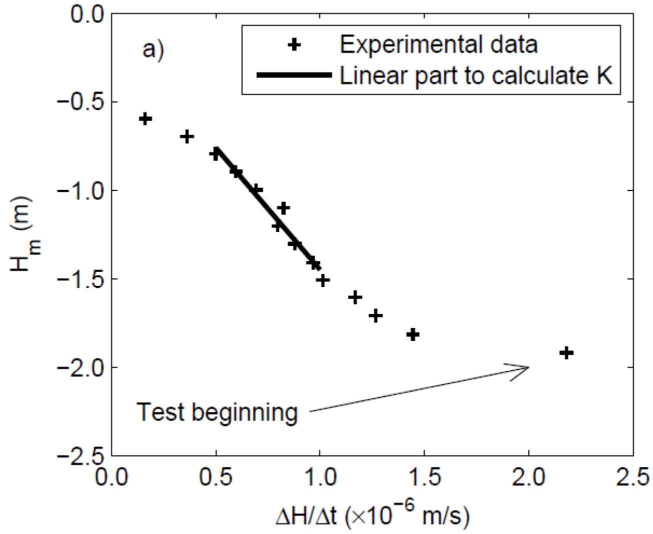
The hydraulic head data for two MWs were applied as a distant boundary condition for the numerical slug tests (Fig. 4). The hydraulic head profile for the upper MW on site 2 was selected because it is smoother than the other profiles, thus avoiding the numerical issues associated with sharp changes in boundary conditions. With its 0.69-m amplitude, this profile is however not representative of the maximum amplitude in Lachenaie. Sites that are located near a river valley show amplitudes that can exceed 2 m. Slug tests conducted in these MWs should show a greater influence of seasonal hydraulic head changes. To verify this hypothesis, simulations were conducted with the hydraulic head profile for the lower MW of site 6. This profile has a 2.9-m amplitude.

3.2. Influence of seasonal hydraulic head cycles on the velocity graph

Figure 5a shows one of the 61 field velocity graphs that were obtained for slug tests with d = 52.5 mm in Lachenaie. This velocity graph corresponds to a rising-head test with an initial hydraulic head of $H(t=0)$ = -2 m. This test was conducted in July of 2010 in the lower MW of site 9, a site located on top of a slope overlooking the Cabane Ronde Brook, in Lachenaie. It can be observed that the velocity graph consists of three parts.

The first part of the velocity graph (high velocity values at the bottom right corner of the graph) shows a curvature due to clay deformation (Duhaime and Chapuis, 2014). In Lachenaie, for slug tests with d = 52.5 mm, the initial curvature usually corresponds to at least the initial 48 hours. The first four data points on Fig. 5a, those that were excluded from the linear trend, correspond to the first 8 days of data at the beginning of the test.

The initial curvature is caused by the high initial hydraulic gradient in the clay adjacent to the sand pack. For a perfectly rigid soil, after initiating the test, the h field around the intake zone would instantly follow the solution to Laplace's equation. However, because the soil skeleton in clay is compressible, a change in h implies a change in pore pressure and mean effective stress. This change in mean effective stress requires a pore volume change in the soil. This deformation is not instantaneous as a finite volume of water must flow into the pore space. Since the pore pressure does not increase instantaneously in the soil, the mean gradient and the flow rate between the MW and the soil are initially higher than those associated with the shape factor definition of Eq. 4 and the solution to Laplace's equation.



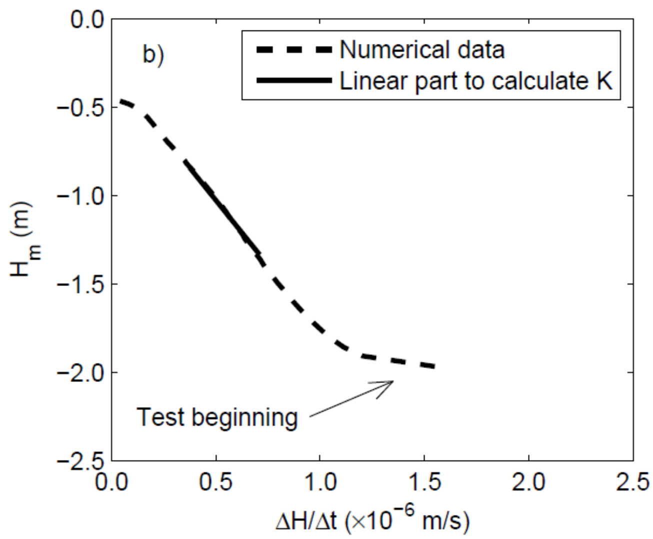


Fig. 5. Experimental (a) and numerical (b) velocity graphs showing the impact of clay deformation and seasonal head changes.

The initial curved part is followed by a straight part which should be used to determine *K*. The *K* value is calculated from the slope of this straight line. All 61 tests with d = 52.5 mm in Lachenaie presented a straight line after the initial curvature.

For long duration tests such as those presented in this paper, the velocity graph can comprise a third part (last two data points to the upper left on Fig. 5a) which is also curved, but this time due to the seasonal hydraulic head cycles shown in Fig. 4. With $d = 52.5$ mm, variable-head tests have a duration of a few weeks. During this period, the background h value in the low-permeability soil can change by more than 100 cm according to Fig. 4. As a consequence, the apparent H_m value does not necessarily go back to 0. The rate of water level change also does not necessarily tends toward 0 as the water level will keep changing after the slug test to follow the annual hydraulic head cycle.

For the experimental velocity graph shown on Fig. 5a, we can infer that the hydraulic head in the clay decreased during the test. The straight part of the velocity graph corresponds to H_0 = -0.07 m. This value indicates that the seemingly static water level before the test was overestimating the value of h in the clay. During the test, the water level did not tend toward the h value given by H_0, but toward an even lower water level (around 0.5 m below the static water level). This is consistent with the fact that this test was conducted in July, a relatively dry month in southern Quebec. The piezometric records on Fig. 4 confirm decreasing h values in July.

Figure 5b shows a velocity graph that was obtained for a numerical rising-head test beginning on September 10th 2015 with $H(t=0) = -2$ m. The following clay properties were used in the model: $K = 5.00\times10^{-10}$ m/s and $S_s = 1.96\times10^{-4}$ m^{-1}. The slope and intercept of the straight line gave K = 6.71×10^{-10} m/s and H_0 = -0.29 m. At the end of the simulation, the water level tended toward -0.45 m, in other words 0.45 m below the initial water level.

The numerical velocity graph clearly shows the three sections that were identified for the experimental velocity graph. The initial curvatures obtained for the experimental and numerical velocity graphs are similar. The H_0 value of -0.29 m and the trend toward an even lower final H_m value of -0.45 m implies that the background hydraulic head decreased during the test. This corresponds to the decrease in hydraulic head that begins around July 1st 2015 and ends around November 1st 2015 on Fig. 4b.

The K value calculated from the slope of the numerical velocity graph (6.71×10^{-10} m/s) differs from the value used in the numerical model (5.00×10^{-10} m/s). With a perfect interpretation method, the K value calculated from the numerical test data would be identical to the value used in the model. Part of the difference between the calculated K values and those used in the model comes from the impact of clay volume changes on the middle third of the velocity graph (e.g., Duhaime and Chapuis, 2014). Seasonal head changes can also have an influence on the slope and intercept of the straight line. This influence is appraised in the following section.

3.3. Influence of seasonal hydraulic head cycles on H_0 and K.

A best fit straight line was drawn for the linear portion of each experimental velocity graph. The slope and intercept of each line were used to calculate H_0 and K based on Eqs. 4 and 6. In Lachenaie, for slug tests with d = 52.5 mm, the straight lines usually comprise most of the velocity data for a given test. The experimental velocity graph curvature shown on Fig. 5a can be seen as an upper bound for the Lachenaie dataset. It is less pronounced for most tests.

When corrected for changes in water viscosity between field and laboratory conditions, the geometric mean of all slug tests is 1.7×10^{-9} m/s for a water temperature of 20°C. This value is similar to that obtained with triaxial tests in the laboratory. Field permeability tests produced similar K values for the clay deposit, but the large scale permeability appears to be slightly higher in the upper intact clay sublayer than in the lower layer (Fig. 2), the geometric means being 2.1×10^{-9} m/s and 1.3×10^{-9} m/s respectively.

Figure 6 shows the relationship between the date of beginning of each test, H_0 (Fig. 6a) and the log (base 10) of the K/K_{mean} ratio (Fig. 6b), where K_{mean} is the geometric mean of all K values for a given well. Some data points were not included in Fig. 6a because the information gathered during the first slug tests were not accurate enough.

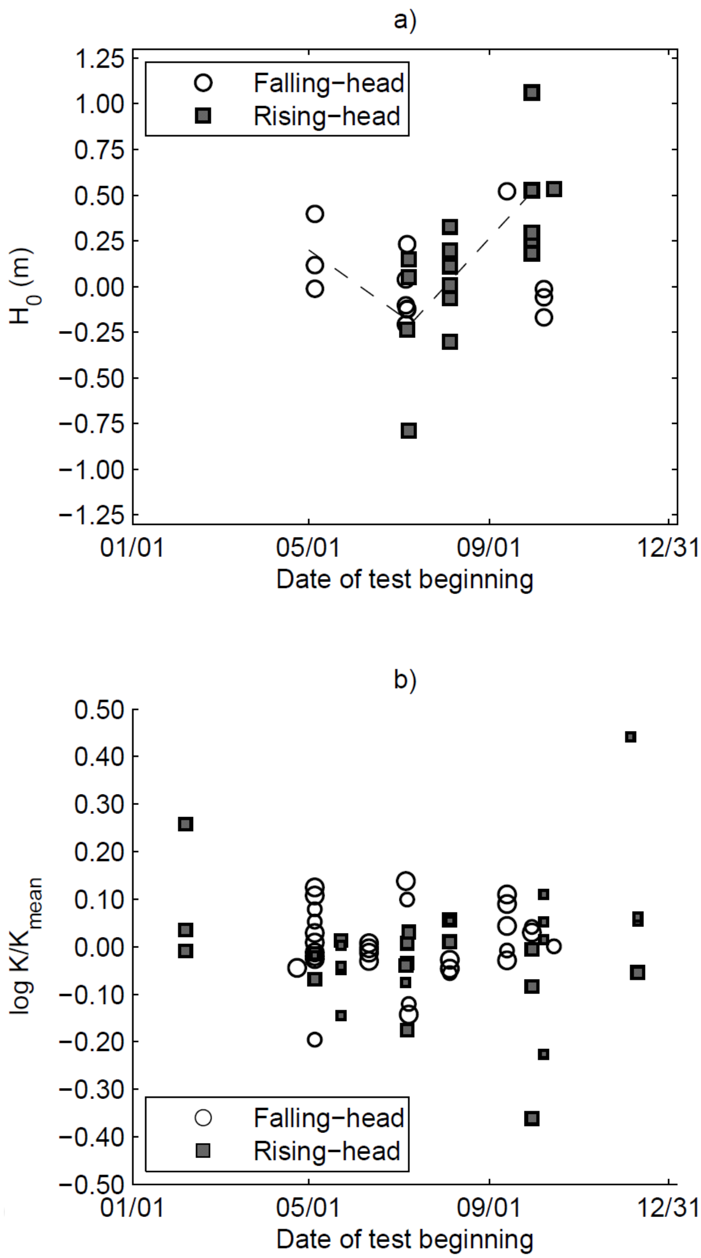


Fig. 6. Experimental values of a) H_0 and b) log K/K_{mean} as a function of the date of beginning of each test and the type of test (rising- or falling-head). On the bottom graph, smaller symbols correspond to absolute $H(t{=}0)$ values that were below 1 m, whereas larger symbols correspond to higher values.

The H_0 and log K/K_{mean} values on Fig. 6 vary respectively between –0.79 and 1.06 m, and –0.36 and 0.44 log cycles. Figure 6a shows that the H_0 values for the Lachenaie dataset were often negative for tests that began in July. Higher values were obtained for tests that began before June or after September. The range of log K/K_{mean} values indicates that the ratio K/K_{mean} varied between 0.43 and 2.76. This implies that an individual test result can differ by a factor higher than 2 from the geometric mean of the K values for the same well. Even if the K values varied, there is no clear relationship between K and the date of beginning of each test (Fig 6b). These observations will now be investigated numerically and then discussed in light of the numerical results.

Figure 7 shows a summary of the H_0 values that were obtained for the numerical slug tests with the hydraulic head boundary measured in the top MW of site 2. When not specified, simulations were conducted with $K = 2\times10^{-9}$ m/s, an initial hydraulic head difference of 1 m (falling-head test) and $S_s = 2\times10^{-4}$ m^{-1}. Figures 7a and 7b respectively show that test parameters such as the type of test (rising- or falling-head) and the initial hydraulic head have little influence on H_0. On both plots, the relationship between H_0 and the dates of test beginning are almost superposed. Both plots also show a tendency for H_0 values to be lower around July. This corresponds to the trend observed for the Lachenaie dataset on Fig. 6a.

Figures 7c and 7d show that clay properties such as hydraulic conductivity and compressibility have more influence on H_0 than test parameters. Figure 7c shows that lower K values tend to accentuate the yearly cycle in H_0 values. Values of H_0 for $K = 5\times10^{-10}$ m/s, a hydraulic conductivity that corresponds approximately to the lowest values in the Lachenaie dataset, reach -0.20 m in July compared to -0.10 m for $K = 2\times10^{-9}$ m/s. This can be explained by the influence of K on slug test duration. Lower K values lead to longer tests. As a consequence, the background hydraulic head in the soil has more time to change and higher absolute H_0 values are observed. Figure 7d shows that higher S_s values lead to higher H_0 values for falling-head tests. This is due to the influence of the initial curvature on the middle part of the velocity graph. Higher S_s values are associated with a more pronounced velocity graph curvature, which tends in return to flatten the velocity graph and to increase H_0 for falling-head tests. The opposite is true for rising-head tests. For them, higher S_s values lead to lower (negative) H_0 values (not shown here).

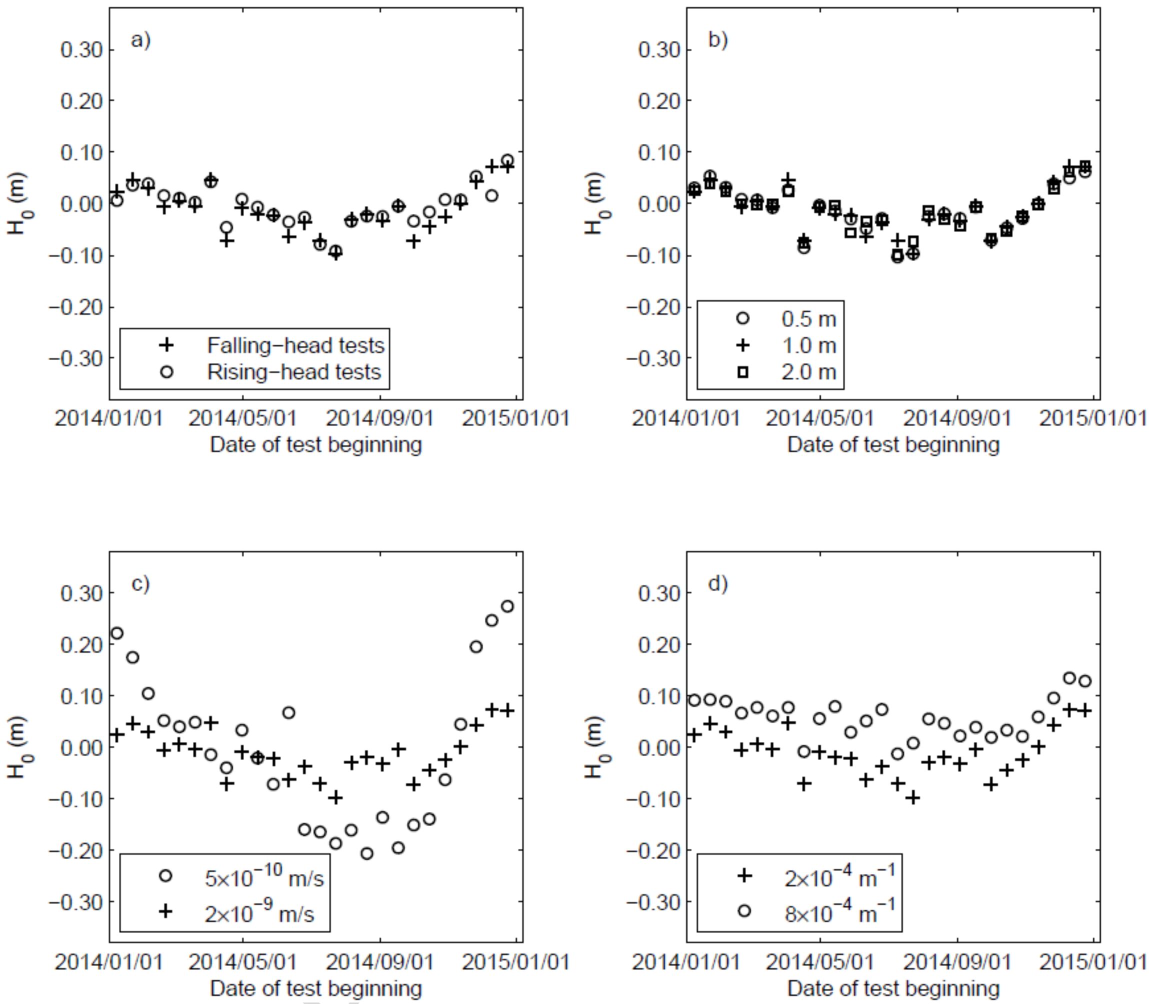


Fig. 7. Influence of test parameters and clay properties on H_0 values for numerical slug tests: a) type of test, b) $H(t=0)$, c) K and d) S_s.

The H_0 trends in Figs. 6 and 7 can be explained in terms of the seasonal hydraulic head cycles (Fig. 4) and general climate observations in Lachenaie and southern Quebec. When H_0 is positive, the initial water level in the MW overestimates the true hydraulic head in the soil. In general, H_0 is positive for tests completed during late spring (May) and autumn (October), two periods of the year with high precipitation, a high water table in Lachenaie, and a river flood. Thus, positive H_0 values are associated with wet periods of the year during which the hydraulic head is increasing in the soil. In the middle of summer (July), H_0 is negative and the water level in the MW is higher than the hydraulic head in the soil. This observation is consistent with the fact that July is a relatively dry month in Lachenaie.

The H_0 trend for the experimental data (Fig. 6) is less clear than the trend observed for the numerical results (Fig. 7). This can be explained by noting that the numerical results (Fig. 7) were obtained based on the assumed seasonal hydraulic head cycle of a specific MW and year. On the other hand, the experimental data were collected in a series of MW over three years. As a consequence, each MWs was affected by a specific background hydraulic head cycle (Fig. 4).

The smaller amplitude for the H_0 cycle in Fig. 7 (less than 0.25 m) compared to Fig. 6a (close to 2 m) can be explained by the choice of boundary condition for the numerical model. Site 2 is located on a flat terrain, far away from rivers, where seasonal hydraulic head cycles have a small amplitude (0.69 m, Fig. 4a) compared to sites that are located near slopes (e.g., 2.9 m on Fig. 4b) close to a river. For this reason, the numerical results presented on Fig. 7 should be seen as a lower bound for the influence of seasonal head changes on slug tests in Lachenaie.

Figure 8 shows the K values that were calculated from the numerical slug test data. Contrarily to H_0, the influence of seasonal head changes on K varies with both test parameters and clay properties. When hydraulic head is decreasing in the clay deposit (e.g., July), Fig. 8a shows that rising-head and falling-head tests respectively lead to higher and lower K values. The opposite trend can be observed when the hydraulic head is increasing (before May and after October). Figure 8b shows that K is more influenced by seasonal head changes when a smaller rapid change in water level, $H(t=0)$, is used to initiate the slug test. With decreasing $H(t=0)$ values, changes in hydraulic head associated with the test become progressively smaller with respect to seasonal head changes. As it was the case with H_0 on Fig. 7c, Fig. 8c shows that the influence of seasonal head changes is more important for low K values, in other words for tests with a longer duration. Finally, also as in Fig. 7d, Fig. 8d shows a systematic influence of S_s on K. In this case, both falling-head and rising-head tests (not shown) lead to higher K values for higher S_s values (softer soil). This can be explained by the influence of soil deformation on the initial curvature of the velocity graph. Soil deformation leads to a more pronounced curvature and a shallower slope for the straight line portion. Equation 6 implies that shallower slopes lead to higher *K* values.

Figure 9 shows how the amplitude of the seasonal hydraulic head cycle influences the numerical *K* values. Simulations for the top MW of site 2 and the bottom MW of site 6 are presented. The simulations are based on $K = 2\times10^{-9}$ m/s, $S_s = 2\times10^{-4}$ m^{-1} and $H(t=0) = 1$ m. As expected, the numerical *K* values obtained for the MW of site 6 are more variable than those obtained for the MW of site 2. The *K* values for sites 2 and 6 span respectively 0.07 and 0.3 log cycle. This confirms that the hydraulic head profile of site 2 gives a lower bound on the influence of seasonal head changes.

Intuitively, higher *K* values could be expected for slug tests that involve a water level change (falling- or rising-head) in the same direction as the seasonal hydraulic head cycle. In other words, a higher *K* value could be expected for a falling-head test conducted in a low-permeability soil where the hydraulic head is also decreasing (e.g., July). The numerical results in Fig. 8a tell otherwise. Higher *K* values were obtained for numerical slug tests that involved a water level change that opposed the seasonal head cycle. This implies that the hydraulic head correction H_0 overcompensates for seasonal head changes. The influence of H_0 on slug tests results is also shown on Fig. 10. This plot compares the numerical *K* values obtained for the same simulations with the velocity graph method and with Eq. 5, in other words with *K* values based on the assumption of a piezometric level equal to the initial water level before the test beginning. The following parameters were used for the numerical slug tests: $K = 2\times10^{-9}$ m/s, $S_s = 2\times10^{-4}$ m^{-1} and $H(t=0) = 0.5$ m. It can be seen that neglecting H_0 effectively leads to higher *K* values when the water level is moving in the same direction as the seasonal head cycle.

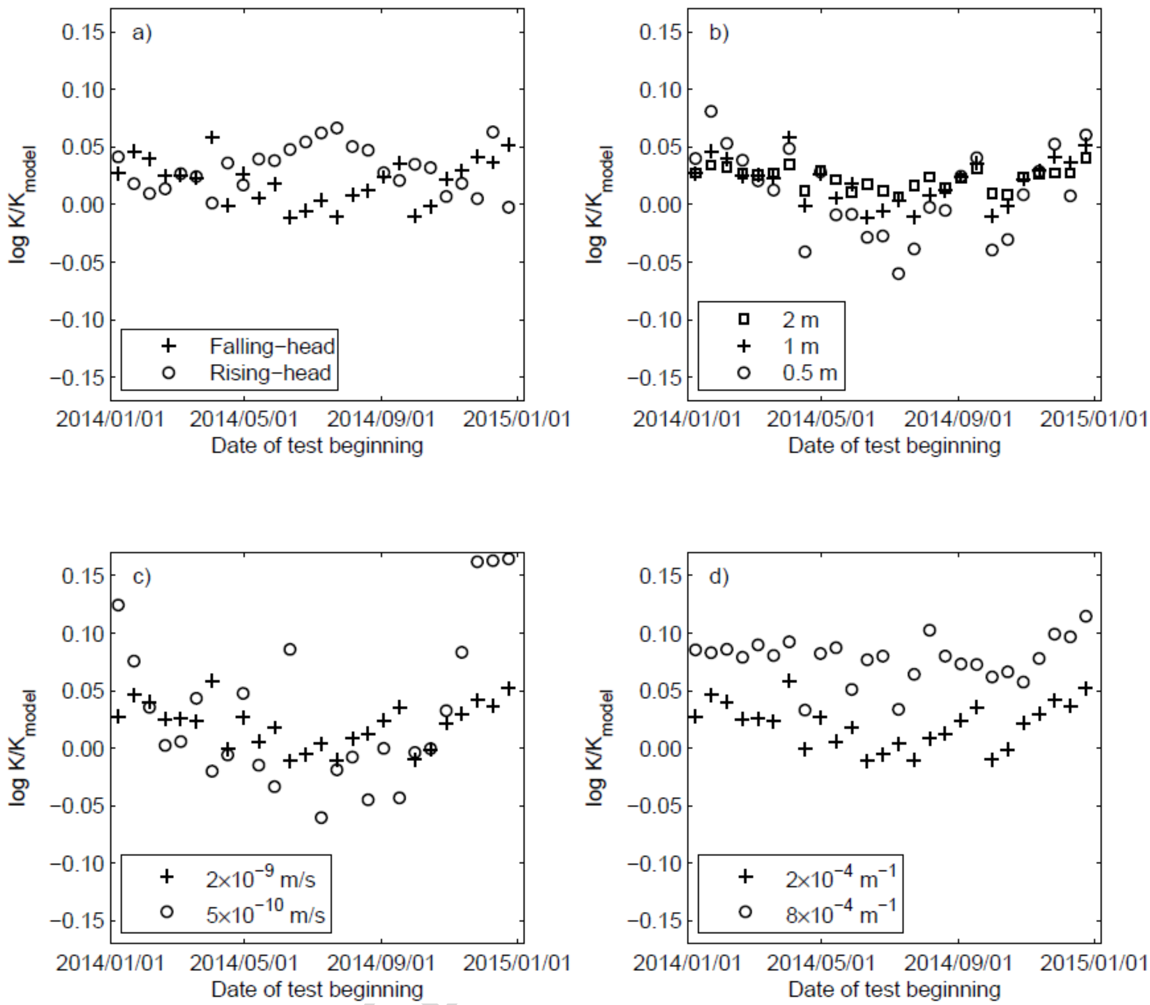


Fig. 8. Influence of test parameters and clay properties on log(K/K_{mean}) values for numerical slug tests: a) type of test, b) $H(t=0)$, c) K, and d) S_s.

As it was the case with H_0, the field K values (Fig. 6b) do not show a pattern as clear as in Fig. 8 for numerical data. Figure 6b distinguishes falling- and rising-head tests, and absolute $H(t=0)$ values below or over 1 m. Rising-head tests conducted in July do not necessarily lead to higher K values as shown by the numerical data on Fig 8a. Smaller $H(t=0)$ values do not result in generally higher K/K_{mean} ratios as on Fig. 8b. Several explanations can be given for this apparent discrepancy. First, Fig. 8 shows that, contrarily to H_0, both clay properties and test parameters have an influence on K. With the experimental results, all these factors vary together and their influence is compounded. Second, as noted for H_0, the numerical results were obtained based on a single boundary condition for a site located on a flat terrain. The phase and amplitude of the hydraulic head cycles tend to differ from one site to another and with depth on a given site. Third, Fig. 6b is based on the ratio between individual K measurement and the geometric mean of as few as 3 tests that were not distributed randomly throughout the year. As a result, K_{mean} is probably biased for some MWs.

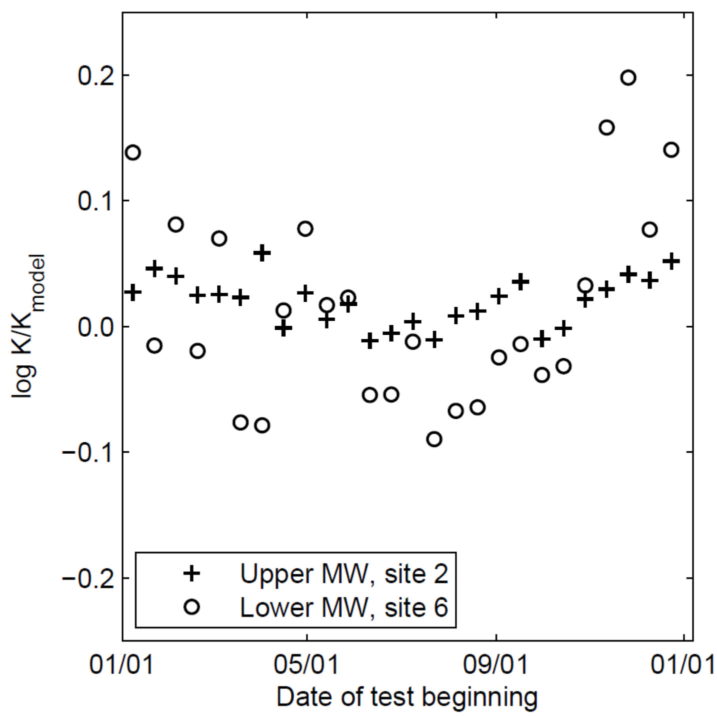


Fig. 9. Influence of amplitude of seasonal hydraulic head cycle on log(K/K_{mean}).

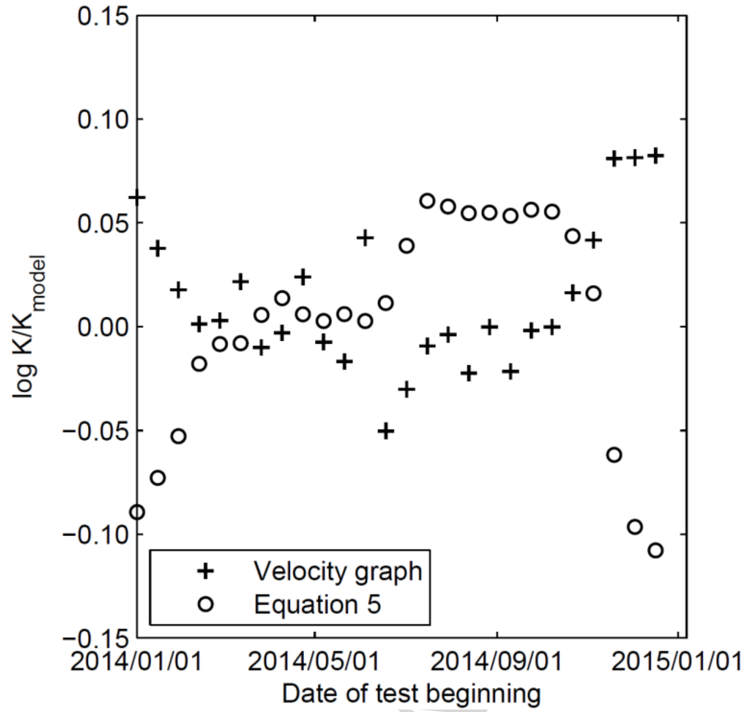


Fig. 10. Comparison of the numerical log(K/K_{mean}) values obtained with the velocity graph and Eq. 5 (K = 2×10^{-9}, S_s = 2×10^{-4} m^{-1}, $H(t$=0) = 0.5 m).

Another approach to compare the experimental and numerical K values is through their variability. How does the variability of numerical results based on constant clay properties but influenced by seasonal head cycles compare with the variability of field results obtained in a real clay deposit with some assumed heterogeneity? Duhaime (2012) looked at the variability of in situ and laboratory K values by fitting lognormal distributions on the different datasets (e.g., Freeze, 1975). Figure 11 presents the cumulative frequency distribution that was obtained for the complete Lachenaie dataset for slug tests with d = 52.5 mm (61 tests), together with cumulative frequency distributions based on 104 numerical slug tests with K = 2×10^{-9} m/s and the hydraulic head cycle of the upper MW of site 2 (Fig 4a), and 104 numerical slug tests with K = 2×10^{-10} m/s and the hydraulic head cycle of the lower MW of site 6 (Fig 4b). All numerical simulations were based on S_s = 2×10^{-4} m^{-1} and $H(t$=0) of -2, -1, 1 and 2 m. As previously shown on Fig 8c, seasonal head changes resulted in a greater variability for lower K values. For the upper MW of site 2 with $K = 2\times10^{-9}$ m/s, and for the lower MW of site 6 with $K = 5\times10^{-10}$ m/s, the best-fit standard deviations for log K were respectively 0.015 and 0.15 log cycles. Because they were based on a constant K, the variability of the numerical results was less than that of the experimental results (0.17 log cycles). Nevertheless, this comparison shows that a significant part of the experimental variability and apparent heterogeneity is due to the influence of seasonal head changes on the experimental results.

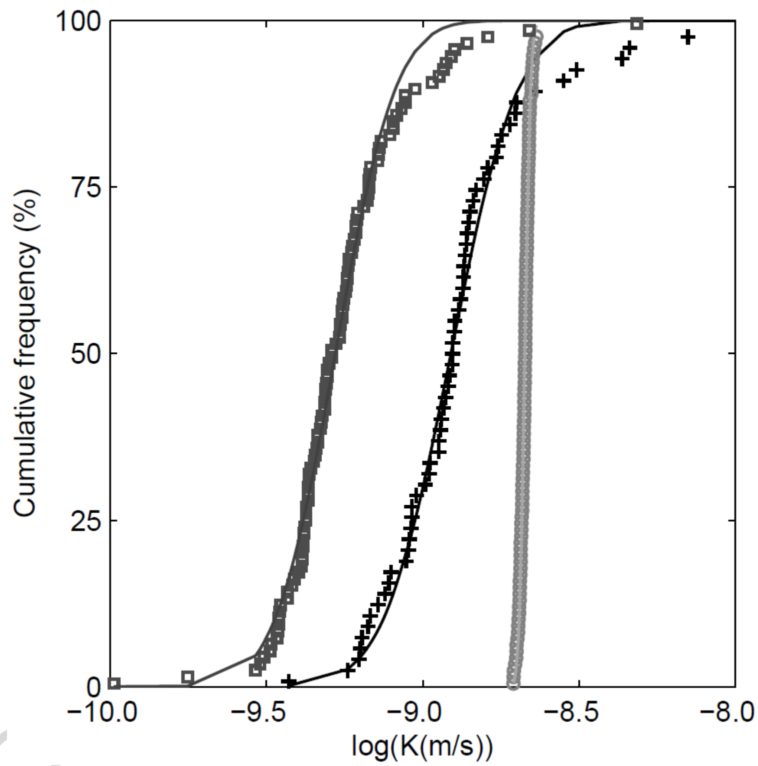


Fig. 11. Apparent lognormal distributions for experimental and numerical *K* values (+: experimental data, □: *h* from site 2 and $K = 2\times10^{-9}$ m/s, ○: *h* from site 6 and $K = 5\times10^{-10}$ m/s, solid lines represent best-fit lognormal distributions).

The K variability due to seasonal head changes can also be compared to the influence of clay deformation on the calculated K value. In this paper, all slug test data were interpreted based on the hypothesis of a perfectly rigid soil skeleton. Based on Eq. 1 and a procedure similar to that used by Duhaime and Chapuis (2014) for pulse tests, Duhaime (2012) corrected each slug test in the Lachenaie dataset for the influence of clay deformation. This influence was always less than a factor 1.1 (0.041 log cycles, see also the $\log(K/K_{\text{mean}})$ values in Fig. 8d). Thus, the influence of deformation on the Lachenaie dataset (d = 52.5 mm) is at least of the same order as the variability associated with seasonal head changes. This is in agreement with the magnitude of the initial and final curvatures for the experimental and numerical velocity graphs shown in Fig 5.

4. Conclusion

The velocity graph method was used in this paper to study the influence of seasonal head variations on the data of field permeability tests conducted in the shallow clay deposit of Lachenaie, Canada. Experimental and numerical velocity graphs were shown to be composed of three parts. The initial curvature is caused by volume changes in the clay. The second part is straight and should be used to calculate K. The third part can also be curved and it is controlled by seasonal head variations. Near the end of the test, as the water level moves progressively closer to the background hydraulic head, the water level stops being influenced by the head change that initiated the slug test and starts following the seasonal head cycle in the low-permeability soil, albeit with a time lag and some dampening.

Seasonal head variations can have a significant influence on the straight portion of the velocity graph for long-duration tests (more than a month). The intercept of the velocity graph (H_0) depends upon the test starting date. Test conducted during dryer months (e.g., July in Lachenaie), tend to produce negative H_0 values. This trend compares well with the hydraulic head time series obtained by Marefat et al. (2015) and with H_0 values obtained for numerical slug tests conducted with a cyclic hydraulic head boundary based on the same experimental hydraulic head time series. The relationship between K and seasonal head variations is more obscure as it is influenced by clay properties and test parameters. The numerical slug tests show that the influence of seasonal head changes on K is directly related to the amplitude of the seasonal hydraulic head cycles. The K variability obtained from the numerical slug tests was shown to represent a significant part of the experimental variability in Lachenaie. The influence of seasonal head changes on K was shown to be at least of the same order of magnitude as the influence of deformation (factor 1.1).

The results presented in this paper have some practical implications. First, because the type of test and its date of beginning have an influence on the apparent K, it is preferable to conduct several tests with different parameters and date of beginning in the same well. If there is a period of the year where hydraulic head fluctuations are smaller, tests should be conducted during this period. Systematically recording and comparing the H_0 values also appears to be a good practice to identify sites that are more likely to be influenced by seasonal head changes. All tests should start with an initial $H(t=0)$ higher than one meter. Using larger hydraulic head difference ($H(t=0)$) could also be suggested as a mean to limit the influence of seasonal head changes on slug tests. However it has significant drawbacks as it tends to increase volume changes for the clay skeleton and the probability of hydraulic fracturing (Bjerrum et al. 1972; Chapuis et al. 1981). Both these issues lead to apparent K values that are overestimated.

Finally, it must be remembered that this paper dealt with a specific subset of field permeability tests: tests conducted in shallow low-permeability soils. Tests conducted in more rigid and permeable materials produce most often straight velocity graphs (e.g. Chapuis and Chenaf 2002; Chapuis 2015). These rapid tests should not be influenced by seasonal head variations, which are slow variations when compared to the duration of the slug tests. With tests conducted in more rigid and permeable materials, Eq. 5 and a shape factor definition based on Eq. 6 will provide accurate K values.

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Highlight

- Impact of seasonal head changes on slug tests in low-permeability soil is studied
- Experimental and numerical results are presented
- Influence of seasonal head changes can be greater than deformation
- Tests parameters, such as initial hydraulic head, have an influence on test results

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