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Influence of seasonal hydraulic head changes on slug tests conducted in shallow low-permeability soils

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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.

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 2 h. 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

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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.

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.

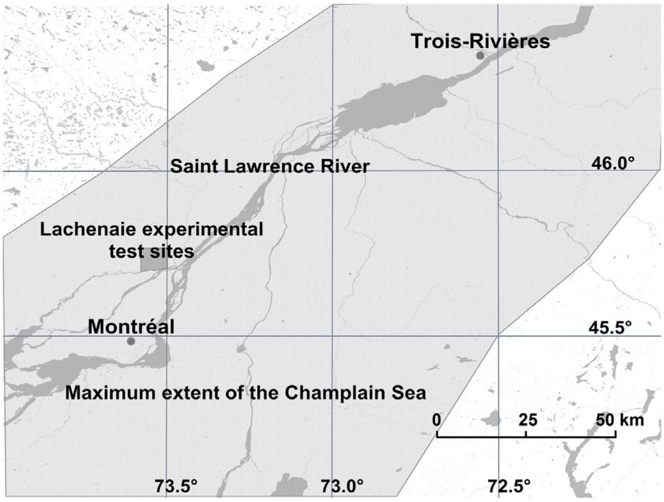

Fig. 1. Location of the Lachenaie experimental test sites within the Champlain Sea basin. (Adapted from Duhaime and Chapuis, 2014).

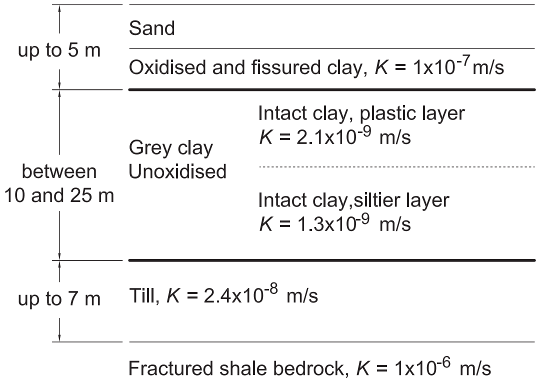

Fig. 2. Simplified stratigraphy and hydraulic conductivity for the Lachenaie test sites.

The 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 min. 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):

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