Vertical Interference Slug Tests for the Measurement of Vertical Hydraulic Conductivity

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ABSTRACT
Numerical modeling of groundwater flow and mass transport requires the knowledge of hydraulic conductivity anisotropy. However, vertical hydraulic conductivity K_v is not commonly measured. This paper proposes vertical interference slug tests in a single well to measure K_v. A field study using different methods to estimate vertical hydraulic conductivity showed that: (1) harmonic means of radial hydraulic conductivity values obtained from high-resolution multilevel slug tests are a poor indicator of the vertical anisotropy in the study area; and (2) values from vertical interference slug tests are in very good agreement with laboratory permeameter *Kv* measurements on soil samples.

RÉSUMÉ
La modélisation numérique de l'écoulement de l'eau souterraine et du transport de masse requière des donées sur l'anisotropie de la conductivité hydraulique. Cependant, la conductivité hydraulique verticale K_v est rarement mesurée. Cette article propose des essais d'interférence verticaux réalisés dans un seul puits afin de mesurer K_v. Une étude de terrain comprenant différentes méthodes d'estimation de K_v montre que : (1) l'utilisation de la moyenne harmonique des valeurs de conductivité hydraulique radiale obtenues d'essais de perméabilité multi-niveaux haute résolution n'est pas un bon indicateur de K_v dans la région d'étude; et (2) les valeurs mesurées par les tests d'interférence verticaux sont très similaires aux mesures de K_v réalisées en laboratoire avec un perméamètre sur des échantillons de sol.

1 INTRODUCTION

Aquifer characterization in support of groundwater flow and solute transport modelling requires the knowledge of hydraulic conductivity anisotropy. However, hydraulic measurements, such as pumping tests, flowmeter profiles and slug test, induce predominantly horizontal flow patterns and therefore only estimate horizontal hydraulic conductivity K_h. This lack of data about vertical hydraulic conductivity K_v often leads to the assumption of isotropic hydraulic conductivity. Unfortunately, such assumptions without field evidence may impact the understanding of an aquifer system, such as the estimation of recharge through aquitards or unconsolidated sediments (Hart et al., 2006), well capture zones (Zlotnik, 1997) and the evolution of contaminant plumes (Falta et al., 2005).

K_v values may be obtained from lab permeameters on soil samples collected in the field. Permeameters involve the flow of water through a core under either constant or variable hydraulic head. Permeameter tests can be carried out either on the original sample, if relatively undisturbed, or on a repacked sample. In either case, careful attention must be taken in all phases of the experimental procedure to preserve or recreate field condition. Recovery of relatively intact core samples may be difficult, especially for unconsolidated sediments (Stienstra and van Deen, 1994). In addition, permeameter tests may be time consuming when many measurements are needed.

The small scale of lab measurements is in general not appropriate for numerical modeling. To measure both K_h and K_v at a more appropriate field scale, Kabala (1993) proposed the dipole-flow test. In the test, two chambers are isolated in the well employing inflatable packers. During the test, water is pumped at a constant rate from one chamber to the other, which generates a circulation of water in the aquifer next to the well. Pressure transducers are installed in the chambers to monitor pressure head changes. Steady state and transient analysis of the dipole-test have been used to estimate aquifer properties (Kabala, 1993; Zlotnick and Ledder, 1996; Zlotnick and al., 2001). However, the solution for both radial and vertical hydraulic conductivity only using pressure head changes is non-unique. To resolve this no uniqueness, Hvilshoj et al. (2000) proposed an inverse numerical multilayer model constrained with pressure responses in the dipole and in adjacent piezometers. Sutton et al. (2000) also proposed to combine a steady-state dipole flow test with a tracer to measure the travel time of the circulation loop between the two chambers. Tandem circulation wells test with and without a tracer was also proposed by Goltz et al. (2008).

However, for most hydrogeological studies, the logistics involved in a dipole test seems too complex. In the petroleum industry, vertical pulse interference tests are used to estimate vertical hydraulic conductivity (Burns, 1969; Hirasaki, 1974; Onur et al., 2004; Sheng, 2009). In a vertical interference test, the basic requirement is that the stress interval and the observation point must be vertically separated in a single borehole. Inflatable packers achieve the separation. The stress interval is a partially penetrating screen where a constant pumping rate is maintained for the duration of the test. The transient pressure data at the stress interval and at the observation point are recorded for the analysis. However, most analytical solutions available for the analysis of vertical pulse interference tests are based on superposition of point source or line source solutions (Burns, 1969; Hirasaki, 1974; Sheng, 2009). Point and line source solutions are not valid for early-test times as the wellbore storage is neglected (Satter et al., 2007). As wellbore storage acts to negatively influence test results, the pumping time should be long enough to dissipate the wellbore storage effects. In shallow aquifers, middle to long-term pumping may be subject to outer boundary conditions, which may lead to erroneous interpretation of the test (Kruseman and de Ridder, 1990). To simulate wellbore storage effects, regression analysis to simultaneously match the pressure responses at the stress interval and the observation point are generally carried out (Onur et al., 2004). Regression analysis however requires the construction of a reservoir model, which is difficult to apply.

As an effective alternative to laboratory testing and existing field tests, this paper proposes a field method to measure vertical hydraulic conductivity. The proposed vertical interference slug test is an adaptation of the inter-well interference slug test (Novakovski, 1989, Liu and Butler, 1995, Spane, 1996, Belitz and Dripps, 1999) to a single well arrangement. The proposed test is a conventional slug test conducted between two isolated intervals of a single well by a three-packer assembly (Figure 1). An instantaneous hydraulic pulse is initiated into a stress screen and responses are measured in both the stress and the observation screen. Under the assumptions of anisotropy and homogeneity, the KGS model (Hyder et al., 1994; Liu and Butler, 1995) is used to estimate specific storage as well as radial and vertical hydraulic conductivity.

This paper first presents a sensitivity analysis with the KGS model on the effects of aquifer properties on vertical interference slug test responses followed by a discussion on the method of analysis. Then, application of the proposed method in a field test is presented and vertical hydraulic conductivity values obtained are compared with high-resolution multilevel slug tests and permeameter measurements done on undisturbed soil samples.

2 SENSITIVITY ANALYSIS-KGS MODEL

A vertical interference slug test can be carried out with several arrangements. Two useful arrangements are illustrated schematically in Figures 1a and 1b. Figure 1a illustrates multiple testing in the same well with a three-packer assembly to isolate two screened intervals. The upper screen is used as the stress screen, while the lower one is the observation screen. In unconsolidated sediments, direct-push wells (Paradis et al., 2010) or hammer-driven wells (Morin et al., 1988) installed without gravel-packs are best suited to avoid hydraulic short-circuits between tested screens. Open boreholes in roc formation may also be used. This assembly can then be used alone to test a single interval or sequentially to test the entire well length. Figure 1b depicts a single interval test between two piezometers isolated into a nested well. With this arrangement, the bentonite between the screens prevents hydraulic short-circuits. Either well can be used as a stress or an observation screen.

The Kansas Geological Survey (KGS) (Hyder et al., 1994; Liu and Butler, 1995) has developed a semi-analytical method for the interpretation of cross-well slug tests in both confined and unconfined settings. The KGS model accounts for elastic storage and anisotropy in the aquifer, wellbore storage in the stress well, partial penetration of the stress and observation wells and the presence of a well skin around the stress well. In this study, the KGS model was used to analyse vertical interference slug tests.

To assess the effects of aquifer properties on the responses of vertical interference slug tests, a sensitivity analysis with the KGS model was carried out. AQTESOLV (V. 4.5) was used for this analysis. The value of individual properties was varied while holding all other properties and parameters constant. The base case used for the sensitivity analysis is for the aquifer properties and test well and aquifer parameters listed in Table 1 and shown in Figure 1a. The test well/aquifer configuration presented is the configuration used for the field test presented in this paper. Semi-log plots were used for the sensitivity analysis even though log-log plots may be more sensitive to aquifer properties effects.

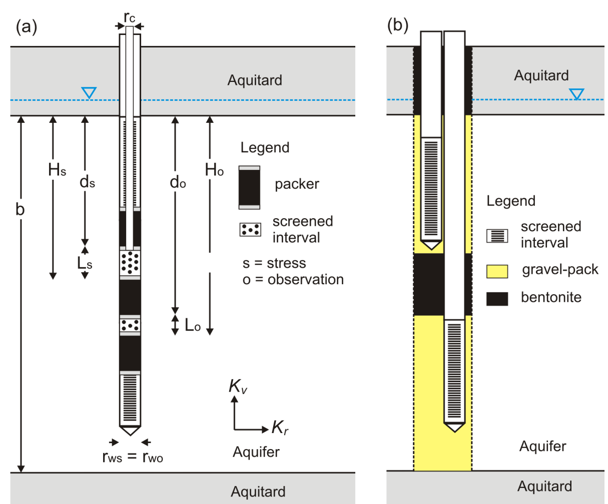

Figure 1. Well arrangement for a vertical interference slug test in a hypothetical confined aquifer: (a) between two isolated screened intervals with a three-packer assembly into a direct-push well; and (2) between two piezometers into a nested well. Subscripts are defined in Table 1.

However, for the range of aquifer properties evaluated in this sensitivity analysis, the effects occur at head levels that would be difficult to detect with existing pressure transducers (0.001 of the maximum head perturbation). Then an analysis with semi-log plots will be more appropriate for most practical applications. Figures 2, 3 and 4 show results of the sensitivity analysis. As expected, varying hydraulic properties causes significant changes in the shape and amplitude of the predicted slug interference responses in both the stress and the observation screen.

Figures 2a and 2b illustrates the influence of radios hydraulic conductivity K_r on the slug interference response in both the stress and the observation screen. As indicated, K_r significantly controls the transmission time of the slug test responses. The relationship between K_r and transmission time is inversely proportional, with higher K_r associated with faster propagation. K_r, however, exerts no effect on shape and amplitude of the response at the stress and the observation screen.

In contrast, Figure 3b shows that specific storage S_s significantly influences the amplitude and shape of the response in the observation screen. S_s also affects the arrival time of the initial response and wave peak amplitude. Lower values of S_s are associated with larger responses and faster response propagation. For the responses in the stress screen, Figure 3a shows only a slight delay at early-test times while late-test times are not affected.

Figure 4b shows the effects of vertical anisotropy on slug test response in the observation screen. As S_s, vertical anisotropy exerts a pronounced effect on the amplitude and shape of the response in the observation screen. In contrast to S_s effects, lower values of vertical anisotropy are associated with smaller responses and slower response propagation. Vertical anisotropy also affects the arrival time of the wave peak amplitude. As shown on Figures 3b and 4b, vertical anisotropy effects are similar to those caused by S_s. Thus, increasing vertical anisotropy is analogous to decreasing S_s. Figure 4a shows that as for S_s effects, vertical anisotropy slightly affects the response in the stress screen. These effects are however exhibited on the late-test times instead of the early-test times for S_s.

As previously shown, vertical anisotropy and S_s have similar effects on the shape and amplitude of the response in the observation screen. For example, Figure 5b and Table 2 show that various combinations of vertical anisotropy and S_s values with the same K_r may result in curves with near identical shapes and amplitudes. Thus, on the basis of the response in the observation screen alone, vertical anisotropy and S_s cannot be distinguished. Figure 5a shows however that the corresponding responses in the stress screen are sensitive to the various combinations of vertical anisotropy and S_s. Thus, stress and the observation screens should be used together to estimate radial hydraulic conductivity, vertical anisotropy and S_s without ambiguity.

3 STUDY SITE AND FIELD WORKS

To demonstrate the use of vertical interference slug tests to estimate vertical hydraulic conductivity K_v, a field study was designed and conducted so as to compare the results with multilevel slug tests and permeameter tests. The comparison was made at well *P17* installed into an aquifer composed primarily of surficial Quaternary sediments that were deposited and reworked by the Champlain Sea (Bolduc, 2003). Based on regional geological data and more than 25 cone penetration tests, the hydrostratigraphy of the aquifer is found to be controlled by the distinctive structure of a spit that formed in a littoral environment. Such a depositional environment leads to the presence of a range of sediment types that range from coarse sand to clayey silt (Figure 6a). Sediment samples often show abrupt transitions in grain-size and the vertical scale of the heterogeneity is more or less a decimetre. Vertical profiles of hydraulic conductivity and hydraulic head measured as part of this study indicate generally semi-confined conditions, which result from alternating sand and silt layers related to the formation of the spit (Figure 6b). The water table is generally 1 to 2 m below ground.

Table 1. Hydraulic properties and parameters used for the base case of the sensitivity analysis. There is no inside radius for the well casing of the observation screen because the screen is isolated with packers. Well coordinates of the observation screen were set close to 0 to simulate the vertical position of the observation screen with respect to the stress screen and to avoid numerical instability.

Aquifer properties	
Radial hydraulic conductivity (K_r)	1×10^{-5} m/s
Specific storage (S_s)	1×10^{-4} m^{-1}
Vertical anisotropy (K_r/K_v)	0.1
Aquifer thickness (*b*)	12 m
Stress test/well parameters	
Static water column height (H_s)	4.56 m
Depth to top of screen (d_s)	3.95 m
Screen length (L_s)	0.61 m
Inside radius of well casing (r_c)	0.0127 m
Inside radius of screen (r_{ws})	0.0254 m
Well coordinates (X/Y)	0/0 m
Observation test/well parameters	
Static water column height (H_o)	5.48 m
Depth to top of screen (d_o)	5.18 m
Screen length (L_o)	0.30 m
Inside radius of screen (r_{wo})	0.0254 m
Well coordinates (X/Y)	0/0.01 m

Table 2. Hydraulic properties for various curves showing similar shapes and amplitudes at the observation screen. Stress and observation screens parameters are presented in Table 1.

Aquifer properties	*Curve 1*	*Curve 2*	*Curve 3*
Radial hydraulic conductivity (K_r) [m/s]	1×10^{-5}	1×10^{-5}	1×10^{-5}
Specific storage (S_s) [m^{-1}]	7.5×10^{-6}	1×10^{-4}	1.3×10^{-3}
Vertical anisotropy (K_r/K_v) [-]	0.01	0.1	1

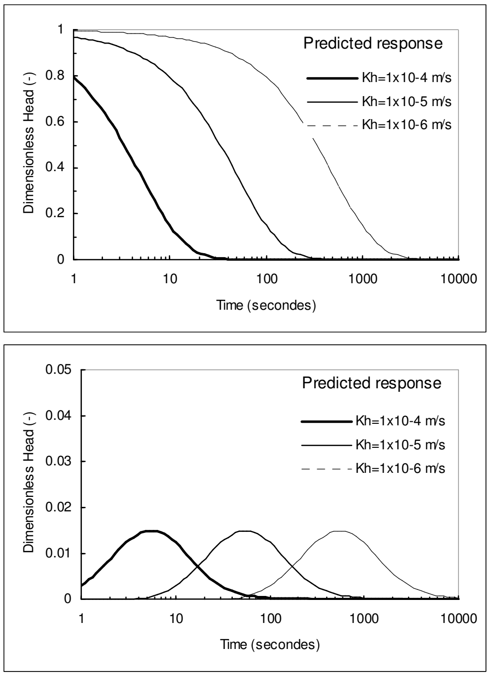

Figure 2. Influence of radial hydraulic conductivity (K_r) on slug test response for: (a) the stress screen; and (b) the observation screen.

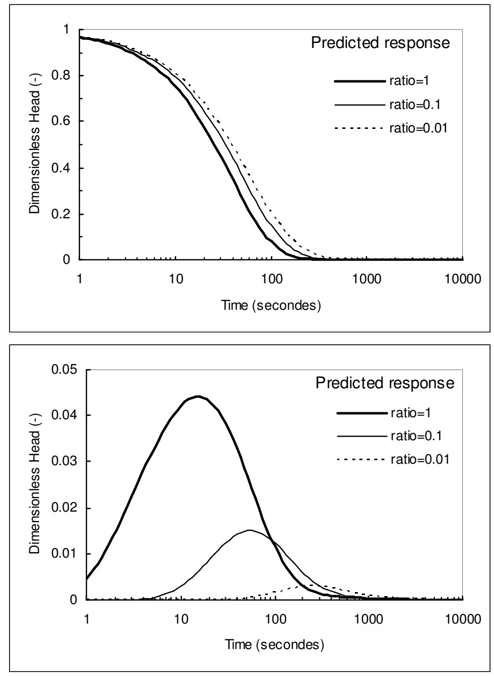

Figure 4. Influence of vertical anisotropy (K_r/K_v) on slug test response for: (a) the stress screen; and (b) the observation screen.

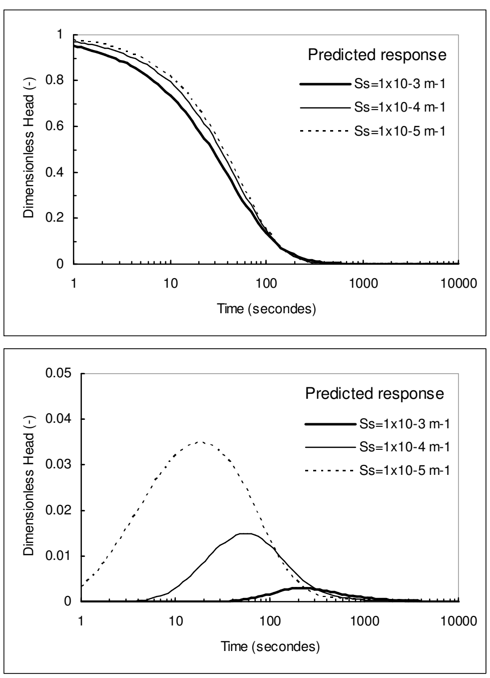

Figure 3. Influence of specific storage (S_s) on slug test response for: (a) the stress screen; and (b) the observation screen.

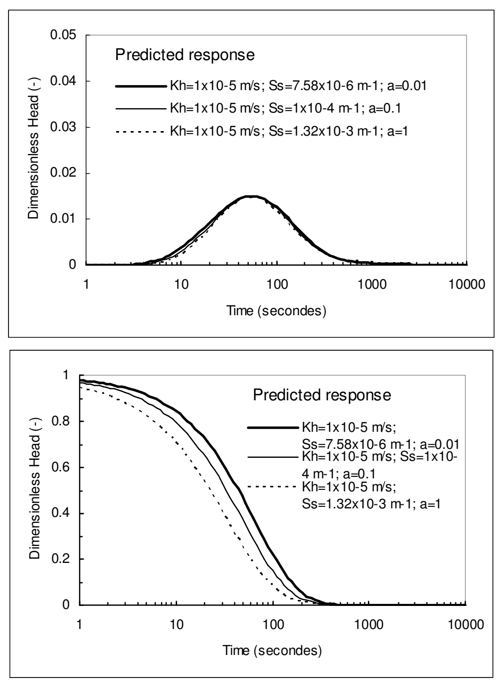

Figure 5. Sensitivity analysis conducted for various combinations of specific storage and vertical anisotropy: (a) in the stress screen, and (b) in the observation screen. This analysis shows the non-uniqueness of the slug test responses in the observation screen.

3.1 Direct-Push Well and Sediments Core Sampling

In this study, the wells used for K_v measurements were installed with a direct-push rig (Geotech 605D) following the protected screen standard technique (ASTM, 2004). Direct-push installations offer advantages over conventional installations in unconsolidated formations: they reduce disturbance to the formation, eliminate drill cuttings and avoid gravel-packs, sediments being instead in direct contact with the screen. Paradis et al. (2010) provide a more detailed description of the direct-push well installation and development.

After well installation and development, sediments were also sampled at a location 1 m from well *P17*. Sampling was carried out with a piston-rod operated sampler (GeoTech Macro-Core Sampler) allowing the recovery inside a PETG liner of a 38 mm diameter and 1.52 m long undisturbed sample. Samples were taken continuously with a direct-push rig (Geotech 605D) over the aquifer thickness and a total of 8 cores were taken. Sediment recovery was 83%.

3.2 Multilevel Slug Tests and Lab Permeameter Tests

Multilevel slug tests were used to establish a vertical hydraulic conductivity profile along well P17. A multilevel slug test involves the use of packers to isolate a screened interval of a well to conduct a slug test (Ross and McElwee, 2007). Multilevel slug tests were made at 15-cm intervals (Figure 6b). A total of 60 K_r estimates were obtained from multilevel slug tests. Paradis et al. (2010) provides a more a detailed description of the assembly and test procedure.

For this study, we also automated a falling head permeameter by installing pressure transducers at the base of multiple falling head devices (reservoir) and recording changes in hydraulic head with time with pressure transducers as proposed by Johnson et al. (2005).

To determine K_v values of soil samples, permeameters were designed to accommodate the 38 mm diameter PETG liner containing soil samples with varying length. This was done to reduce sample manipulation in order to minimize disturbance of original sediments. Each 1.52 m long sample were subdivided into 15 cm long subsamples. The subdivision was done according to the tested intervals with multilevel slug tests and vertical interference slug tests. Subsamples were then compacted at a pressure corresponding to the sampling depth with a hydraulic press. Occasional voids in the undisturbed subsamples were locally repacked to avoid a hydraulic short-circuit along the sample. Each falling head device was placed over a subsample saturated with water at room temperature to initiate a test. The rate of decline of the water level in the reservoir was then used to calculate vertical hydraulic conductivity using a derivation of Darcy's law (Fetter, 1994). The total number of subsamples tested with falling head permeameter was 34. Duplicate tests (2 to 3) carried out on a variety of subsamples indicated a high degree of reproducibility. All hydraulic conductivity values were temperature-corrected to an aquifer temperature of 8°C.

3.3 Vertical Interference Slug Tests

For this study, inflatable packers were fabricated over 2.54 cm ID PVC tubing. Threads on the PVC tubing allowed the use of variable screen lengths between packers. An air line was attached to the packers and connected at the surface to an air compressor to inflate the packers to the desired pressure. The dual-packer assembly was also connected by a 2.54 cm ID PVC riser pipe to the surface, within which water levels were monitored during the slug test. A rigid tape was attached near the top to accurately locate the position of the straddled interval. The screens arrangement used for this study is shows in Figure 1a. The stress and the observation screens are 61 cm and 30 cm long respectively, while the separation between the bottom of the stress screen and the top of the observation screen is 61 cm. Vertical interference slug tests were made at 61 cm intervals whose elevations were coincident with the intervals tested by the multilevel slug tests and the permeameter tests.

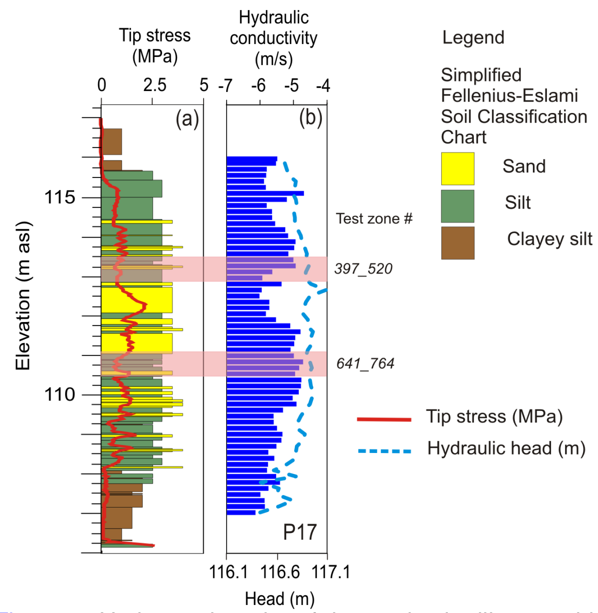

Figure 6. Hydrostratigraphy of the study site illustrated by well *P17* with: (a) cone penetration test; and (b) hydraulic conductivity and static hydraulic head measured during high-resolution (15 cm) multilevel slug tests. Soil textures are defined according to the Fellenius and Eslami (2000) cone penetration test soil classification chart. Also shown is the tip stress, measured during the cone penetration test, and locations of the tested intervals (61 cm) from vertical interference slug tests.

Once the packers are inflated, the pressure transducer positioned into the stress and the observation screens and air pressure stabilization into the test interval a trend-monitoring period was followed to facilitate test interpretation. After this period, slug tests were carried out using a pneumatic method to induce the initial lowering of the water level (Levy and Pannell, 1991). For this purpose, a wellhead assembly was attached to the top of the riser pipe that contained an airtight adapter that allowed a transducer cable to pass and a ball valve for rapid release of pressure. An air compressor was also connected to the wellhead assembly to increase air pressure in the riser. A precision digital air-pressure gauge was used to accurately set the desired initial hydraulic head change for the slug test and to verify air pressure stabilization before initiating the slug test. For each test, the initial drawdown was as high as practical to produce a response in the observation screen that is larger than the head resolution of the pressure transducer. Since peak amplitudes in the observation screen are generally only a few centimetres, heads should be monitored as close as possible with an accurate pressure transducer. As with any slug test, varying and repeated head changes were imposed for quality control and to verify repeatability (Butler et al., 1996). A total of 12 vertical interference slug tests were carried out along well *P17*.

4 ANALYSIS OF VERTICAL INTERFERENCE SLUG TESTS

To estimate vertical hydraulic conductivity, the KGS model was applied on two relatively homogeneous but anisotropic intervals along well *P17* (Figures 6). Figures 7a and 7b show the match between observed head responses and the KGS model for interval *397_520*. This match was obtained by simultaneously matching the responses in the stress and the observation screens. Vertical anisotropy value obtained for this interval was 0.041 for an estimated vertical hydraulic conductivity value of 5.74×10^{-7} m/s (Table 3).

Results of the match for interval *641_764* in the stress and the observation screens are presented in Figures 8a and 8b respectively. In contrast with the previous interval, the early-test times in the observation screen suggests the influence of a leak. This leak may be explained by two ways. First, a high-permeability skin may have been created around the screen during well development activity. As well *P17* was used to test different well development configurations; this may have removed an excessive amount of fines particles in the vicinity of the screen. Second, the high cohesion of some sediments such as clayed silt layers may have prevented the complete collapse of the sediments during the direct-push well installation. As the leak speeds up early-test times, the data match was done for late-test times data measured beyond the peak amplitude. Vertical anisotropy value obtained for this interval was 0.0061 for an estimated vertical hydraulic conductivity value of 1.24×10^{-7} m/s (Table 3).

5 COMPARISON OF VERTICAL INTERFERENCE SLUG TESTS WITH OTHER METHODS

The accuracy of the results obtained from vertical interference slug tests can be partly assessed by comparing them to values obtained using multilevel slug tests and laboratory permeameter. Multilevel slug tests and permeameter measurements were obtained at a vertical resolution of 15 cm while vertical interference slug tests were carried out on 61 cm long interval. For the comparison with vertical interference slug tests, an equivalent vertical hydraulic conductivity was calculated for multilevel and permeameter tests by applying a harmonic mean on the four 15 cm intervals comprise into each 61 cm of the vertical interference slug tests.

The comparison in Table 4 of vertical hydraulic conductivity values obtained from high-resolution multilevel and vertical interference slug tests shows one to two orders of magnitude of discrepancies. The small-scale heterogeneity of the sediments may explain this strong difference. As multilevel slug tests induce predominantly horizontal flow patterns, the presence of thin horizontal low permeability layers does not reduce significantly the radial hydraulic conductivity estimation (parallel flow). In contrast, these low permeability layers essentially control the flow in the vertical direction (serial flow). Then multilevel slug tests at a vertical resolution of 15 cm are poor indicators of the vertical anisotropy in this environment. To be useful for vertical hydraulic conductivity estimation, the vertical resolution of the tests should be as small as the heterogeneity of the sediments (around 1 cm), a situation that would be impracticable.

Table 3. Stress and observation screens parameters and aquifer hydraulic properties obtained by vertical interference slug tests for intervals *397_520* and *641_764*. Stress and observation screen locations are shown in Figures 6.

Test no.	***397_520***	***641_764***
Aquifer properties		
Radial hydraulic conductivity (K_r) [m/s]	1.40×10^{-5}	2.03×10^{-5}
Specific storage (S_s) [/m]	5.50×10^{-5}	1.06×10^{-5}
Vertical anisotropy (a=K_r/K_v) [-]	0.041	0.0061
Vertical hydraulic conductivity (K_v) [m/s]	5.74×10^{-7}	1.24×10^{-7}
Stress screen parameters		
Observed initial displacement (*Ho*)	2.83 m	4.83 m
Static column height (*H*)	3.34 m	5.78 m
Depth to top of screen (*d*)	2.73 m	5.17 m
Screen length (*L*)	0.61 m	
Radius of well casing (r_c)	0.0127 m	
Inside radius of screen (r_w)	0.0254 m	
Well coordinates (*X*/*Y*)	0/0 m	
Observation screen parameters		
Static column height (*H*)	4.26 m	6.70 m
Depth to top of screen (*d*)	3.96 m	6.40 m
Screen length (*L*)	0.30 m	
Radius of screen (r_w)	0.0254 m	
Well coordinates (*X*/*Y*)	0/0.0254 m	

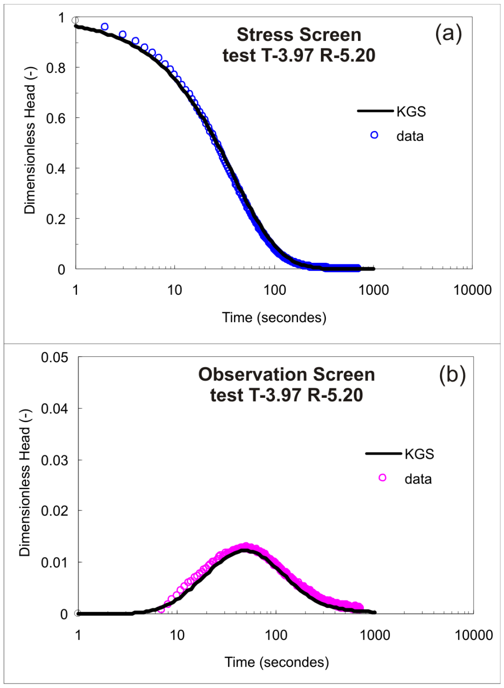

Figure 7. Observed vertical interference slug test response and data match with the KGS model for test *397_520* in: (a) the stress screen; and (b) the observation screen.

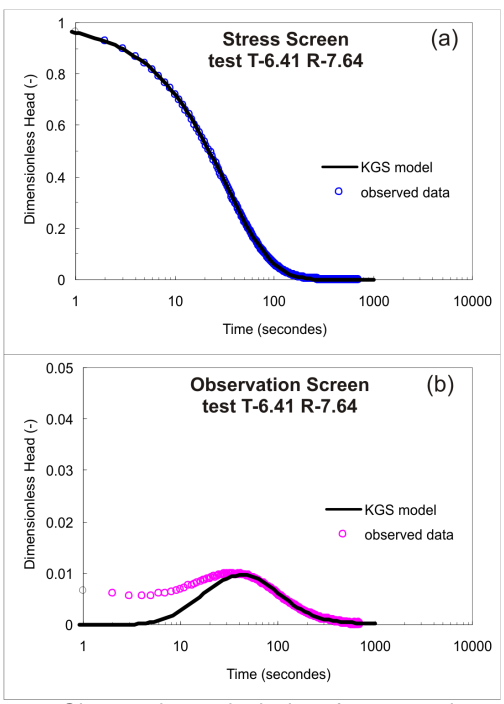

Figure 8. Observed vertical interference slug test response and data match with the KGS model for test *641_764* in: (a) the stress screen; and (b) the observation screen.

Table 4 shows that vertical hydraulic conductivity values obtained from the vertical interference slug tests are in very good agreement with permeameter tests for the same tested intervals. Vertical interference slug tests values for the two tested intervals are respectively 1.95 and 0.87 time the values of the permeameter tests. Table 3 also shows that vertical hydraulic conductivity values obtained with vertical interference slug tests are between 2 to 3 orders of magnitude lower than radial hydraulic conductivity. This is in agreement with the depositional environment of the study area, where large grain-size transitions are often observed in sediments samples. As the vertical anisotropy is large for this particular context, this stresses the importance of adequately characterizing vertical hydraulic conductivity. As already reported by Zlotnik (1994), ignoring vertical anisotropy will result in an underestimation of the radial hydraulic conductivity. For the two intervals presented in this paper, the calculated radial hydraulic conductivity increased by 44% and 58% respectively when vertical anisotropy was taken into account.

Table 4. Summary of hydraulic tests used to estimate vertical hydraulic conductivity. The tested interval for vertical interference slug tests is 61 cm in length. A harmonic mean is applied on 15 cm hydraulic conductivity sub-sample and sub-interval for permeameter and multilevel slug tests.

Test no.	Vertical Hydraulic Conductivity (m/s)		
	Multilevel Slug Test	**Permeameter**	**Vertical Interference Slug Test**
397_520	2.69×10^{-6}	2.95×10^{-7}	5.74×10^{-7}
641_764	1.28×10^{-5}	1.41×10^{-7}	1.24×10^{-7}

6 CONCLUSIONS

A field method was developed to measure vertical hydraulic conductivity into a single well. The method is an adaptation of cross-well interference slug tests and the KGS analytical model was used for analyzing the tests. A sensitivity analysis on the effects of aquifer properties showed that vertical anisotropy and specific storage have similar effects on the test response in the observation screen. Then for homogeneous aquifer, both response in the stress and the observation screens should be used to estimate vertical anisotropy, radial hydraulic conductivity and specific storage without ambiguity. A field example was also described in which a comparison was made between vertical interference slug tests, high-resolution multilevel slug tests and permeameter tests on undisturbed sediments samples. This comparison showed that vertical hydraulic conductivity values obtained with the proposed method are in very good agreement with permeameter tests for the same tested intervals. However, radial hydraulic conductivity values obtained with high-resolution multilevel slug tests are poor indicators of the vertical anisotropy in this environment.

Thus with adequate well installation, vertical interference slug tests could be an effective method to estimate vertical hydraulic conductivity as well as radial hydraulic conductivity and specific storage. The method may be easily implemented during multilevel slug testing. An additional observation screen may be simply added below the conventional assembly used to conduct multilevel slug tests. However, the major limitation of vertical interference slug tests is the presence of leaks or skins around the screen. In unconsolidated aquifers, direct-push wells installed without gravel pack or nested piezometers may provide the necessary for those tests.

In the future, an improvement of the method to estimate vertical hydraulic conductivity will be required for heterogeneous profiles. In this paper, the usefulness of the proposed method was applied only to homogeneous material, i.e. when the stress and the observation screens were in the same material. The adaptation of the analysis procedure using the KGS model or a modification of it will be done. A procedure using regression model could be also proposed. Other work will be done to assess the influence of leaks or skins on the tests results. This would be done with a numerical model of the aquifer and well/test parameters.

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