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Numerical assessment of the direct-push permeameter for investigation of small-scale variations in hydraulic conductivity

LUDWIG ZSCHORNACK[1], GEOFFREY C. BOHLING[2], JAMES J. BUTLER, JR[2] & PETER DIETRICH[1]

1 Helmholtz-Centre for Environmental Research -UFZ, Permoserstrasse. 15, 04318 Leipzig, Germany
ludwig.zschornack@ufz.de

2 Kansas Geological Survey, University of Kansas, 1930 Constant Avenue, Lawrence, Kansas 66047, USA

Abstract Characterization of hydraulic conductivity (K) variations on the scale of relevance for transport investigations is one of the main challenges faced in groundwater investigations. Recent work has shown that direct-push technology has great potential for providing high-resolution vertical profiles of subsurface parameters (e.g. K) in shallow unconsolidated formations. The direct-push permeameter (DPP) is a particularly promising tool for hydrostratigraphic characterization, but our understanding of its performance in highly heterogeneous formations is far from complete. This work is directed at advancing our understanding of DPP performance in highly heterogeneous media. We evaluate DPP potential through a series of numerical simulations using a heterogeneous configuration that is based on a previous aquifer analogue study. Our results demonstrate that the DPP can provide reliable K profiles, even in the presence of vertical K variations on the decimetre scale, and that the DPP configuration has a significant influence for the characterization of smaller-scale variations in K.

Key words hydrostratigraphic characterization; model parameterization; direct push

INTRODUCTION

Small-scale variations in hydraulic conductivity (K) can significantly affect solute transport in the saturated zone (e.g. Boggs *et al.*, 1993; Barth *et al.*, 2001; Zheng & Gorelick, 2003). Due to the lack of field methods to accurately characterise small-scale heterogeneities in K, the parameterization of groundwater models, particularly those for contaminant transport applications, is still a challenge. The estimation of hydraulic parameters in highly heterogeneous media on scales of relevance for transport investigations is difficult to accomplish with traditional field methods. For example, the long-established pumping test provides K estimates that are averaged over a relatively large volume of the aquifer (Butler, 2009). The sampling and sieve analyses of core material has the potential to provide information at the needed scale, but is cost- and time-intensive due to the significant effort required in both the field and the laboratory. Furthermore, the uncertainty in K estimates from grain-size data can be large due to the site-specific nature of the empirical relationships (e.g. Vienken & Dietrich, 2011). As a result, further research is needed to develop field methods that are suitable for the efficient and reliable characterization of spatial variations in K. The direct-push permeameter (DPP) and the recently developed high-resolution K (HRK) tool show great potential for the high-resolution characterization of vertical variations in K in heterogeneous aquifers (Lowry *et al.*, 1999; Butler *et al.*, 2007; Liu *et al.*, 2009). Although previous simulation investigations have characterised DPP performance under varying conditions (Lowry *et al.*, 1999; Liu *et al.*, 2008), additional work is needed to improve the understanding of DPP performance in highly heterogeneous aquifers. This is our focus here.

In this work, we use high-resolution numerical modelling of DPP hydraulic tests to investigate the reliability of the K estimates calculated from DPP profiling in highly stratified aquifers. We evaluate the value of information about vertical variations in K that can be obtained from DPP tests in highly heterogeneous aquifers using a form of Darcy's law, without additional or elaborate data analysis (e.g. numerical inversion). We also compare the results from different DPP configurations to assess the impact of probe configuration on K estimates in heterogeneous aquifers.

THE DIRECT PUSH PERMEAMETER

The general principle of the DPP has been described by several authors (e.g. Lowry *et al.*, 1999; Butler *et al.*, 2007; Liu *et al.*, 2008). The DPP probe typically consists of a short screened section at the bottom of the rod string with two pressure transducers a short distance above the screen (Fig. 1). As the probe is advanced into the subsurface, water is injected through the screen to prevent clogging. When the desired depth for a *K* estimate is reached, advancement and water injection are suspended. After heads have returned to background levels, a number of hydraulic tests are performed by injecting water through the screened section, while recording pressure responses at the transducers on the probe rod. Two or more different flow rates are used for quality control purposes (Butler *et al*., 2007). A *K* estimate can then be obtained using the spherical form of Darcy's law (e.g. Butler *et al*., 2007):

$$K = \frac{Q}{4\,\pi(\varDelta h_1 - \varDelta h_2)}\left(\frac{1}{l_1} - \frac{1}{l_2}\right) \tag{1}$$

where Q is the rate of water injection, $\varDelta h_1$ and $\varDelta h_2$ are the pressure changes at the transducer 1 and 2, l_1 and l_2 designate the distance from the first and second transducers, respectively, to the midpoint of the injection screen. The equation requires steady-shape conditions, i.e. the injection-induced head gradient between the transducers has stabilized. In general, the gradient reaches its final steady-state value before the heads themselves reach steady state. The DPP also allows for the estimation of *K* using only one of the transducers. Such a test can be useful for the identification of thin layers between the transducers or if one of the transducers malfunctions during a test (Butler *et al*., 2007). The following equation provides the *K* estimate for a test with a single transducer *i*:

$$K_i = \frac{Q}{4\,\pi\, l_i(\varDelta h_i)}. \tag{2}$$

In this case, the equation requires that steady-state conditions, i.e. heads no longer changing with continued injection, are attained. Since steady-shape conditions are usually reached more rapidly than steady-state conditions, a DPP test using two transducers requires less time than a test with one sensor, especially in formations of relatively low *K* (Butler *et al*., 2007; Liu *et al*., 2008).

NUMERICAL SIMULATION OF DPP PERFORMANCE IN A HETEROGENEOUS AQUIFER

Model set-up

An axisymmetric cylindrical finite-difference model of groundwater flow in response to a DPP test under confined conditions was used for the simulations of this work (Bohling & Butler, 2001). The model solves the following steady-state flow equation, which is also applicable at any given time once steady-shape conditions have been attained (Liu *et al*., 2008):

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rK_r\frac{\partial h}{\partial r}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right) = 0 \tag{3}$$

where h is the hydraulic head, r and z are the radial and vertical coordinates, and K_r and K_z are the hydraulic conductivities in the radial and vertical directions, respectively. The model is discretised into 100 cells (equal logarithmic spacing) in the radial direction and 400 cells (equal linear spacing) in the vertical direction. The log-transformed radial increment $\varDelta r'$ was set to 0.1, resulting in a distance of 5.65×10^2 m to the outer boundary. In our initial simulations, the vertical spacing was set to $\varDelta z = 0.01$ m for a higher resolution assessment and to $\varDelta z = 0.025$ m for a lower resolution. In all the simulations, *K* was specified as a known parameter and anisotropy was set to 1.0 for all cells. A constant injection rate of 6.0×10^{-5} m^3/s was used for all simulations, consistent with the rate used in previous field investigations (e.g. Butler *et al*., 2007; Liu *et al*., 2009). The computed hydraulic heads under steady-state conditions were used to calculate the pressure head gradient between the transducers under steady-shape conditions. The *K* distributions used in the simulations were based on the heterogeneous K distributions obtained in a previous aquifer analogue study of the Herten gravel pit in Baden-Württemberg, Germany (e.g. Tronicke *et al*., 2002; Bayer *et al*., 2011). That analogue study illustrates the complex hydrogeology of the sedimentary deposits and the consequent variability in hydraulic parameter values (Fig. 2). For our simulations, we only used the changes in K along the two vertical profiles (white columns) marked on Fig. 2. Given the very limited radius of investigation of the DPP (Liu *et al*., 2008), we ignore the lateral variations in K depicted in Fig. 2.

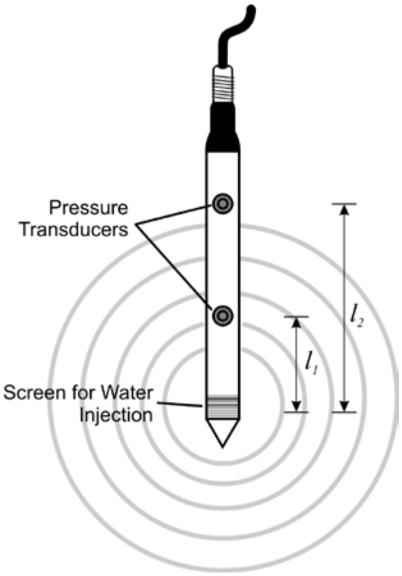

Fig. 1 Schematic representation of the direct-push permeameter. The distances between the injection screen and the pressure transducers were varied during the simulations.

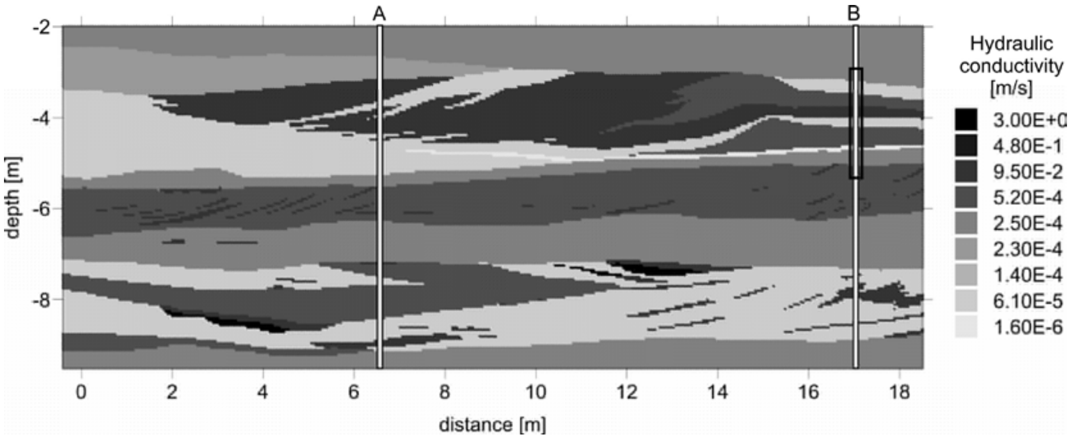

Fig. 2 Heterogeneous K distribution from the Herten gravel pit. The figure illustrates the complex K distribution arising from the different vertical and horizontal sedimentary structures and sequences. The vertical white columns indicate the locations of the profiles investigated in this work; the black rectangle in the upper part of the right profile indicates the interval simulated with two discretisation schemes (after Tronicke *et al*., 2002).

RESULTS

The first set of simulations was performed to assess the influence of vertical discretisation (Δz = 0.025 m and Δz = 0.01 m) on the estimated K values. The smallest K layer used in the model was

0.05 m so we needed to evaluate how many cells are appropriate for an accurate simulation of the effect of such small-scale heterogeneities. For this assessment, we used a relatively heterogeneous part of the profile B in Fig. 2 (black rectangle). Injection tests were simulated every 0.025 m for the low (Δz = 0.025 m) as well as for the high-resolution (Δz = 0.01 m) model. The results of these simulations differ slightly (Fig. 3). The differences are small relative to the absolute changes in *K* along the profile, and are most pronounced in the vicinity of the two low *K* layers at depths of ~4 m and ~4.75 m. Given the small differences between the profiles, the 0.025 m discretisation was used for the remaining simulations reported here.

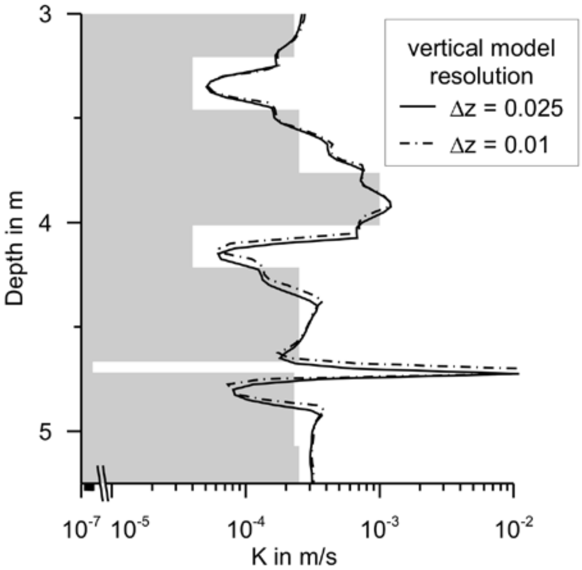

Fig. 3 Comparison of numerical simulation results using two spatial discretisation schemes. The depth is assigned to the midpoint between the centre of the injection screen and the closest pressure transducer. The location of the vertical interval is marked by the black rectangle of profile B in Fig. 2.

The second set of simulations was performed to assess the dependence of *K* estimates on the probe configuration (transducer location) for a constant separation distance (0.1 m) between the transducers. The simulations were performed along the two vertical profiles of Fig. 2 with a vertical interval of 0.05 m between the locations at which DPP injection tests were simulated. The results reveal that the DPP provides a reasonable representation of the vertical variations in *K*, except in the vicinity of very thin layers (Fig. 4). It is also evident that different DPP configurations produce different *K* profiles. The probe configuration with the shortest distance between the pressure transducers and the injection screen produced the most accurate *K* values and patterns. In intervals with only minor variations in *K*, both configurations produced *K* values that were close to those used in the model. In other parts of the profiles, however, inaccurate and contradictory results are obtained. These occur in the vicinity of thin layers of relatively low *K*, which appear as high *K* layers in the *K* estimates from the numerical simulations. The configuration in which the distance between the pressure transducers and the injection screen is large produced the largest deviation from the *K* used for the simulations. Thus, the relationship between layer thickness and the distance between the injection screen and the pressure transducers is a key factor for the characterization of *K* variations. This finding is important when considering hydrostratigraphic units that are expected to have thin layers of relatively low *K* and is consistent with results previously reported by Liu *et al*. (2008).

The third set of simulations was performed as a more detailed assessment of the dependence of DPP *K* estimates on the probe configuration. For these simulations, we used the profile B of Fig. 2. In the first group of these simulations, we kept the closest pressure transducer at a constant

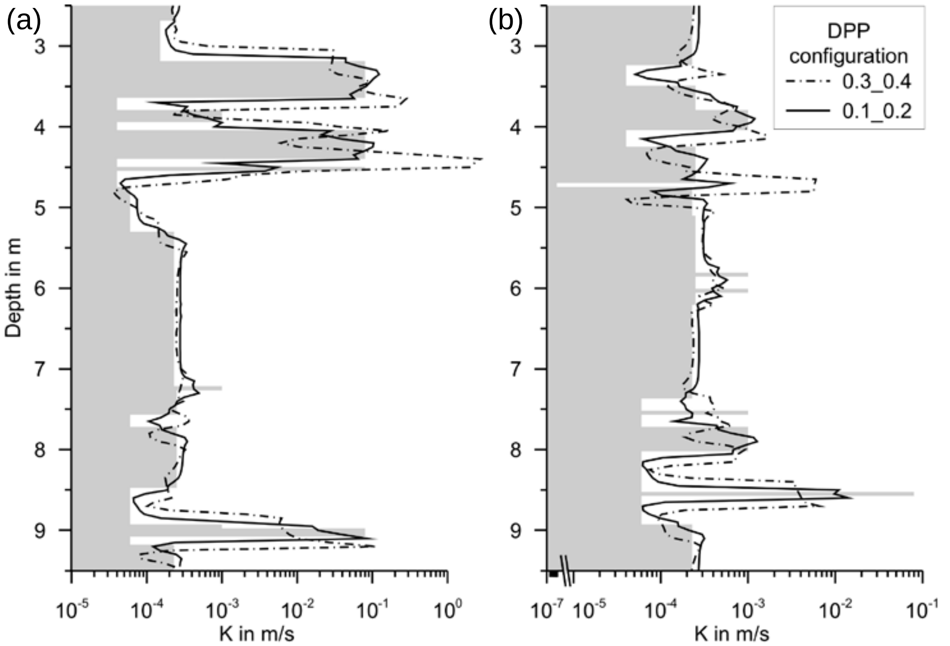

Fig. 4 Vertical profiles (a) and (b) of the model-input *K* (grey region) and that estimated from the results of the numerical simulations of DPP tests for different distances between pressure transducers and the injection screen (l_1–l_2); distance between transducers kept constant (0.1 m) in all simulations. The *K* estimates were assigned to a depth midway between the injection screen and the closest transducer.

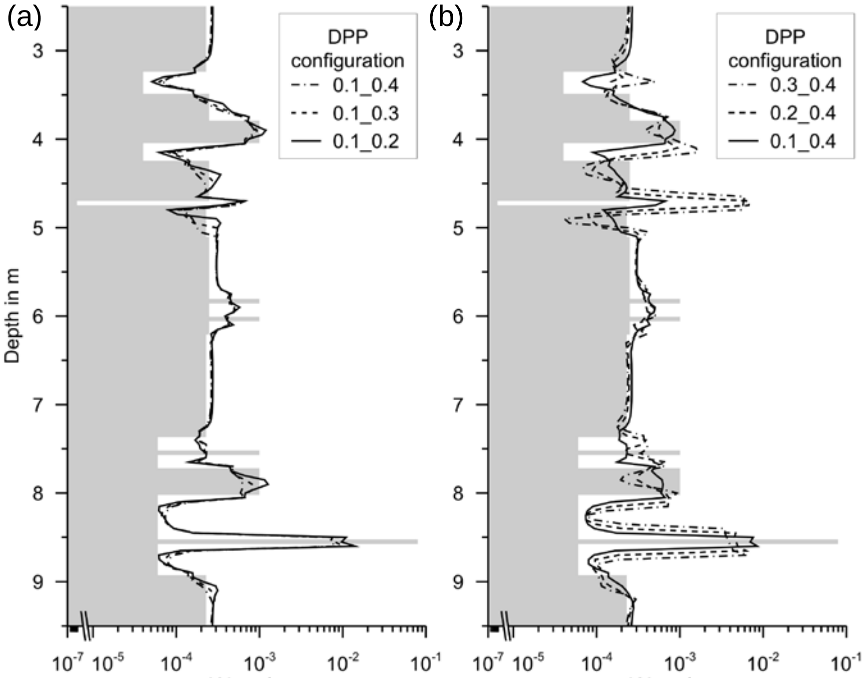

Fig. 5 Vertical profiles of the model-input *K* (grey region) and that estimated from the numerical simulations of DPP tests for different distances between the pressure transducers and the injection screen (l_1–l_2): (a) for a constant distance to the closest pressure transducer (0.1 m), and (b) for a constant distance to the furthest transducer (0.4 m). The *K* estimates from each DPP test are again assigned to a depth midway between the injection screen and the closest transducer.

distance of l_1 = 0.1 m from the injection screen while the other transducer was moved along the probe. In the second group of these simulations, we reversed the arrangement and kept the furthest transducer at a distance of $l_2 = 0.4$ m from the injection screen while the other transducer was moved along the probe. Injection tests were again simulated every 0.05 m. The results reveal that changes between *K* profiles were small when the distance between the injection screen and the furthest pressure transducer was systematically increased (Fig. 5). The distance between the injection screen and the closest transducer is more critical for the accuracy of the *K* estimation of thin *K* layers. However, none of the probe configurations in Fig. 5 were able to accurately characterise the thin (≈0.05 m thick) low *K* layer situated at ~4.75 m depth. In contrast, the analogously thin (≈0.05 m thick) high *K* layer at a depth of ~8.5 m is characterised relatively well. Thus, it appears that thin layers with high *K* can be characterised more accurately than thin low-K layers. However, the interpretation of such thin high *K* layers in a DPP profile is ambiguous since a low *K* layer with a similar thickness would produce similar results (Fig. 5). Without further information on the *K* structure at the decimetre to centimetre scale, even a high-resolution DPP *K* profile can provide misleading results when small-scale heterogeneities occur in the aquifer. Thus, as Liu *et al*. (2008) recommended, injection pressures should be monitored continuously during probe advancement (water injected during advancement to prevent screen clogging) to provide additional information to constrain the interpretation of DPP profiles.

CONCLUSION

The results of our numerical assessment demonstrate that the DPP can provide consistent, high-resolution profiles of *K* in very heterogeneous aquifers. Vertical variations of *K* on the scale of decimetres can be identified and characterised relatively well. However, an accurate characterization of the *K* of very thin (scale of centimetres) layers using equation (1) is more problematic. In particular, thin layers of relatively low *K* can produce paradoxical results. In these cases, the DPP tends to overestimate the *K* value by several orders of magnitude. Thus, a thin low-*K* layer can inadvertently be misinterpreted as a layer of relatively high *K*. We also found that the probe configuration with the smallest distance between the closest pressure transducer and the injection screen provides the most accurate results, even for *K* variations on the decimetre scale. Therefore, the DPP configuration is a key factor for spatially resolving and characterising small-scale heterogeneities in *K*.

This work is ongoing and future investigations will include more detailed assessments of DPP performance, probe configuration, and behaviour under transient flow. We will examine the influence of horizontal changes in K associated with sedimentary/aquifer structures (e.g. cross-bedding), and will investigate numerical inversion approaches as a means of characterising vertical variations in *K* using the DPP.

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REFERENCES

Barth, G. R., Hill, M. C., Illangasekare, T. H. & Rajaram, H. (2001) Predictive modelling of flow and transport in a two-dimensional intermediate-scale, heterogeneous porous medium. *Water Resour. Res.* 37(10), 2503–2512.

Bayer, P., Huggenberger, P., Renard, P. & Comunian, A. (2011) Three-dimensional high-resolution fluvio-glacial aquifer analog: Part 1: Field study. *J. Hydrol.* 405 (1–2), 1–9.

Boggs, J. M., Young, S. C., Beard, L. M., Gelhar, L. W., Rehfeldt, K. R. & Adams, E. E. (1992) Field study of dispersion in a heterogeneous aquifer: 1. Overview and site description. *Water Resour. Res.* 28(12), 3281–3291.

Bohling, G. C. & Butler, J. J., Jr. (2001) lr2dinv: A finite-difference model for inverse analysis of two-dimensional linear or radial groundwater flow. *Computers & Geosciences* 27(10), 1147–1156.

Butler, J. J., Jr. (2009) Pumping tests for aquifer evaluation-time for a change? *Ground Water* 47(5), 615–617.

Butler, J. J., Jr., Dietrich, P., Wittig, V. & Christy, T. (2007) Characterizing hydraulic conductivity with the direct-push permeameter. *Ground Water*, 45(4), 409–419.

Liu, G., Bohling, G. C. & Butler, J. J. Jr. (2008) Simulation assessment of the direct-push permeameter for characterizing vertical variations in hydraulic conductivity. *Water Resour. Res.* 44(2), W02432.

Liu, G., Butler, J. J. Jr., Bohling, G. C., Reboulet, E., Knobbe, S. & Hyndman, D. W. (2009) A new method for high-resolution characterization of hydraulic conductivity. *Water Resour. Res.* 45(8), W08202.

Lowry, W., Mason, N., Chipman, V., Kisiel, K. & Stockton, J. (1999) In situ permeability measurements with direct push techniques: Phase II topical report. *SEASF-TR-98-207* Report to DOE Federal Energy Technical Centre.

Tronicke, J., Dietrich, P., Wahlig, U. & Appel, E. (2002) Integrating GPR and cross-hole radar tomography: A validation experiment in braided stream deposits. *Geophysics* 67, 1495–1504.

Vienken, T. & Dietrich, P. (2011) Field evaluation of methods for determining hydraulic conductivity from grain size data. *J. Hydrol.* 400(1–2), 58–71.

Zheng, C. & Gorelick, S. M. (2003) Analysis of solute transport in flow fields influenced by preferential flowpaths at the decimetre scale. *Ground Water* 41 (2), 142–155.