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Sensitivity analyses of the theoretical equations used in point velocity probe (PVP) data interpretation

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ABSTRACT

Point velocity probes (PVPs) are dedicated, relatively low-cost instruments for measuring groundwater speed and direction in non-cohesive, unconsolidated porous media aquifers. They have been used to evaluate groundwater velocity in groundwater treatment zones, glacial outwash aquifers, and within streambanks to assist with the assessment of groundwater-surfaced water exchanges. Empirical evidence of acceptable levels of uncertainty for these applications has come from both laboratory and field trials. This work extends previous assessments of the method by examining the inherent uncertainties arising from the equations used to interpret PVP datasets. PVPs operate by sensing tracer movement on the probe surface, producing apparent velocities from two detectors. Sensitivity equations were developed for the estimation of groundwater speed, v_∞, and flow direction, α, as a function of the apparent velocities of water on the probe surface and the α angle itself. The resulting estimations of measurement uncertainty, which are inherent limitations of the method, apply to idealized, homogeneous porous media, which on the local scale of a PVP measurement may be approached. This work does not address experimental sources of error that may arise from the presence of cohesive sediments that prevent collapse around the probe, the effects of centimeter-scale aquifer heterogeneities, or other complications related to borehole integrity or operator error, which could greatly exceed the inherent sources of error. However, the findings reported here have been shown to be in agreement with the previous empirical work. On this basis, properly installed and functioning PVPs should be expected to produce estimates of groundwater speed with uncertainties less than $\pm$15%, with the most accurate values of groundwater speed expected when horizontal flow is incident on the probe surface at about 50° from the active injection port. Directions can be measured with uncertainties less than 15° with the most accurate measurements occurring when the flow angles are relatively low – on the order of 20°. At still lower flow angles, quantitation may suffer due to experimental limitations related to tracer delivery. However, useful qualitative assessments of α may still be possible under these conditions.

1. Introduction

The point velocity probe (PVP) is a relatively recent technology for measuring groundwater velocity in noncohesive, saturated sediments (Labaky et al., 2007). A growing body of work is establishing PVPs as viable and useful additions to hydrogeologic characterization projects (Labaky et al., 2009; Schillig et al., 2011; Devlin et al., 2012; Kempf et al., 2013). In addition to a velocity quantification range of at least 0.03 m/day to 30 m/day (Schillig et al., 2011; Schillig et al., 2016), an advantage of PVPs is that they offer an independent check on more conventional methods of estimating groundwater velocity. In some cases, particularly those associated with contaminant movement in groundwater, alternatives to Darcy-based calculations, which depend on knowledge of the uncertain and scale dependent hydraulic conductivity parameter, may be highly desirable for a proper assessment of water movement. The combined use of traditional and 'direct' groundwater velocity methods (i.e., PVPs in this case) was shown to be of practical value in the identification of a highly permeable sediment stratum in a glacial outwash aquifer in Ontario, Canada, where in situ denitrification was studied as a possible short-term nitrate remediation strategy to preserve a municipal water supply (Critchley et al., 2014; Schillig et al., 2016). Prior to the PVP measurements, conventional aquifer testing led to predictions that groundwater was moving about 2 m/day. Multilevel PVP testing indicated the presence of a stratum conducting water at more than 10 times that rate. That finding was later checked with an independent bromide tracer test that utilized multilevel monitors to sample locations above, below, and within the high permeability stratum. The observed tracer velocities clearly supported the probe findings. The presence of the fast zone was important for the proper design of the in situ treatment system.

PVPs may also prove useful in cases where the groundwater velocity in small areas is of interest, such as across small sites, or in reactive zones in aquifers. In such cases, the uncertainty in hydraulic

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conductivity is joined by challenges measuring the hydraulic gradient accurately; water level differences in closely spaced wells may not vary more than their measurement errors. Notably, this concern can also apply to some well networks with larger well spacings. Where *K* is large, the resistance to flow is low and very small gradients are sufficient to achieve typical groundwater flow rates. For example, Devlin and McElwee (2007) demonstrated that well separation distances had to exceed 100 m for reliable gradient measurements in a flood plain aquifer on the Kansas River, where the *K* was estimated to be about 1×10^{-3} m/s. The importance of groundwater velocity measurements, as discussed above, justifies further development of direct measurement methods.

PVP performance has been evaluated in the laboratory and in the field (Labaky et al., 2007; Labaky et al., 2009; Kempf et al., 2013). In controlled laboratory sand-tank tests, PVP velocity estimates were compared to those derived from pumping rates, Q ($L^3\ T^{-1}$),

$$v_{expected} = \frac{Q}{An} \tag{1}$$

where A is the cross-sectional area (of the tank) perpendicular to flow (L^2) and n is porosity (dimensionless). Here, L refers to units of length and T to units of time. The deviations of PVP velocity estimations from $v_{expected}$ averaged ±9%, with a maximum reported error of 37% in one test (Labaky et al., 2007). Flow direction was estimated to be measureable within 15°. The source of the error was attributed to experimental limitations in achieving homogeneous conditions in the packing of the sand around the probes. In the field, Labaky et al. (2009) used Eq. (1) in a sheet pile bounded alleyway of the C.F.B. Borden aquifer to estimate a bulk groundwater velocity through the alleyway of about 20 cm/day. In one location in the alleyway a PVP was used to measure velocities at 11 different depths. The measurements varied from 20 cm/day to 67 cm/day with the variations in velocity as a function of depth matching those in hydraulic conductivity determined by permeametry. The average flow direction over all 11 depths was within about 6° of the expected value. The average groundwater speed measured by PVPs was 34.7 cm/day. The differences in average velocity values between PVP and bulk values of $v_{expected}$ were duplicated with independently conducted Geoflowmeter measurements, suggesting that departures from $v_{expected}$ in the PVP measurements were due to aquifer variability rather than method biases.

Kempf et al. (2013) compared groundwater velocities from several methods, including PVPs, in a sand aquifer beside a tidally influenced river. They determined that the bulk velocity on the site, determined from Darcy's Law calculations (not Eq. (1)), ranged from 0.04 to 12.8 m/day and that flow was on average to the southeast at about 159° measured clockwise from north (approximate range was from 140° to 210°). The work was challenged by tidally imposed reversals in hydraulic gradient that occurred on the site. The PVPs were constructed with single injection ports to measure flow to the southeast or east toward the river. Measurements from three locations yielded velocities ranging from 0.17 m/day to 0.94 m/day with an average flow direction of 110° clockwise from north (range was between 52° and 152° clockwise from north). These results do not match the Darcy-derived results exactly because the temporally variable flow affected the different measurement scales somewhat differently. Nevertheless, the results are comparable and generally consistent. Kempf et al. (2013, pg. 55) found that "The results of both flow velocity and direction calculated by Darcy's Law are consistent with the range of the PVP results." Thus, in this case the PVP data both compliment and support the flow interpretation from head data.

The experiences reviewed above establish a favorable PVP performance compared to Darcy-based velocity estimation in the laboratory and the field. The prior work assigned the observed uncertainties in velocity primarily to experimental artifacts related to variations in the porous medium and difficulties in knowing exactly what the 'true' velocities were for comparison. Schillig et al. (2014) addressed a further contributor to experimental error by quantitatively examining the effects of tracer density flow on the PVP velocity estimates. They found that tracer concentrations up to 5 g/L NaCl could be used in sand aquifers without sacrificing the probe performance. Guidance was provided for minimizing biases due to density flow of the tracer. Nevertheless, it remains to be shown that uncertainties arising from the theoretical equations used in PVP analyses (see Eqs. (2) and (3)), i.e., uncertainties inherent to the method, can be discounted. Therefore, in this work the PVP equations were examined to evaluate the sensitivity of groundwater velocities to the apparent velocities measured at the detectors, and to the estimated flow directions. This work establishes minimal levels of uncertainty to be expected when using PVPs, and permits evidence of errors larger than the inherent ones – due, for example, to borehole irregularities, flow transience during testing, operator error, signal interferences at the detectors, or other site-specific causes of uncertainty – to be properly ascribed to experimental factors. It must be emphasized that experimental causes of uncertainty may vary on a case-by-case basis and may greatly exceed the inherent uncertainties (discussed in this work), which is the case for most field measurements by any method. Experimental sources of uncertainty can be assessed through replicate tests and comparisons of PVP velocity estimations with those from other, independent, methods (see, for example, Schillig et al., 2016). The findings from this work can assist with both PVP design and deployment to achieve the most reliable velocity estimates possible with PVPs.

1.1. Overview of velocity measurements with PVPs

Details of the methods used to conduct groundwater velocity measurements with PVPs are available elsewhere (Labaky et al., 2009; Devlin et al., 2009; Devlin et al., 2012; Kempf et al., 2013). Briefly, a PVP is placed between sections of well casing (typically 5.08 cm outside diameter), such that the assembly forms a continuous impermeable cylinder. Multiple PVPs can be placed onto a single assembly. A borehole is prepared by pushing a hollow drill rod (~7 to 8 cm inside diameter) into the ground to a depth matching the length of the assembly. The rods are usually flushed to remove sediment as they are advanced. They are kept full of water to prevent heaving of the aquifer material into their open bottoms once the descent is complete. The assembly, with tracer solution preloaded in the injection lines, is then lowered into the hollow rods, displacing water. The rods are pulled back while holding the assembly stationary. The collapsing sediment at the bottom of the borehole locks the assembly into place. In non-cohesive sediments, the PVPs become packed in place with the collapsing aquifer material. Some degree of sediment disturbance inevitably occurs next to the probe but, as reviewed in the Introduction, field testing has shown that in noncohesive deposits the resulting biases are generally small compared to potential sources of uncertainty from more conventional velocity determinations.

PVP testing is accomplished by injecting approximately 0.25 mL to 1 mL of tracer solution onto the probe surface and tracking the progress of the tracer as it is carried around the probe by groundwater. This is typically achieved by using tracers with electrical conductances different from the ambient groundwater, and tracking them with at least two electrical conductivity detectors on the probe. The resulting breakthrough curves are recorded for each detector and are used to calculate apparent tracer velocities that vary with the angular position of the probe in the flow system. The apparent velocities also vary with the ambient speed of the groundwater. A single PVP can be built with up to three tracer injection ports positioned symmetrically on the device. The 3-port probes are have no 'blind spots' and are therefore useful where flow directions vary in time (on scales larger than a single test), or when they are not well known in advance of installation, since at least one injection port is always placed in a position to measure flow,