ground water

Methods Note/

A Wet/Wet Differential Pressure Sensor for Measuring Vertical Hydraulic Gradient

by Brad G. Fritz[1] and Rob D. Mackley[2]

Abstract

Vertical hydraulic gradient is commonly measured in rivers, lakes, and streams for studies of groundwater–surface water interaction. While a number of methods with subtle differences have been applied, these methods can generally be separated into two categories; measuring surface water elevation and pressure in the subsurface separately or making direct measurements of the head difference with a manometer. Making separate head measurements allows for the use of electronic pressure sensors, providing large datasets that are particularly useful when the vertical hydraulic gradient fluctuates over time. On the other hand, using a manometer-based method provides an easier and more rapid measurement with a simpler computation to calculate the vertical hydraulic gradient. In this study, we evaluated a wet/wet differential pressure sensor for use in measuring vertical hydraulic gradient. This approach combines the advantage of high-temporal frequency measurements obtained with instrumented piezometers with the simplicity and reduced potential for human-induced error obtained with a manometer board method. Our results showed that the wet/wet differential pressure sensor provided results comparable to more traditional methods, making it an acceptable method for future use.

Introduction

Measurement of vertical hydraulic gradient (VHG) in rivers, streams, and lakes is a common approach for determining the direction and rate of water movement at the sediment–water interface. This is particularly important in studies focusing on groundwater–surface water interaction. Measurement of VHG has been used in numerous studies to determine the direction of water movement at a location, or combined with hydraulic conductivity to calculate discharge or recharge rate at the sediment–water interface (e.g., Harvey and Bencala 1993; Cey et al. 1998; Fryar et al. 2000; Pretty et al. 2006).

Traditionally, several approaches have been used to measure VHG in river settings. The installation of shallow piezometers or minipiezometers in combination with river stage gauges to measure hydraulic head elevation at the surface and in the subsurface is one common method. Using this method, VHG can be determined by physically measuring the difference in height between the surface water and the water column in the piezometer using a graduated electrical contact meter, chalked wire, or other apparatus (Anderson et al. 2005; Baxter et al. 2003; Geist et al. 2002). Similarly, piezometers can be outfitted with electronic pressure sensors to automatically record head elevations (Welch and Lee 1989; Fritz and Arntzen 2007; Geist et al. 2008; Hanrahan 2008). Another common method for determining VHG, which was first suggested by Lee and Cherry (1978), is a hydraulic potentiomanometer or a manometer board. This method typically uses a minipiezometer installed into the subsurface, with a manometer connected to the minipiezometer and a stilling well in the surface water (Woessner and Sullivan 1984; Winter et al. 1988; Conant 2004) to directly measure the differential pressure between the surface and the subsurface. Some researches have used a light

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oil manometer to magnify the head difference, allowing for higher resolution measurements (Kelly and Murdoch 2003), while others have added multiple channels to a manometer board to evaluate VHG in minipiezometer bundles (Acworth 2007).

Both of these two methods of VHG measurement have been successfully implemented in the field; however, there are some limitations associated with each method. One advantage of the manometer board method is that the VHG is determined by recording only two measurements: (1) the distance from the substrate surface to the screen and (2) the difference in head between the surface and subsurface. This allows simple, accurate measurements of VHG to be made quickly. However, the use of a manometer board provides only a single point-in-time measurement. The installation of piezometers for continuous measurements using pressure sensors overcomes these temporal limitations. However, uncertainty in VHG calculated with a piezometer-based method is largely a function of user-induced measurement errors (not sensor errors); use of piezometers and pressure sensors requires multiple depth and elevation measurements, introducing more potential sources of error.

In this paper, we describe the application of a self-contained wet/wet differential pressure sensor and integrated data logger to directly measure and record the VHG. This combines the advantage of high-temporal frequency measurements of VHG obtained with instrumented piezometers with the simplicity and reduced potential for error obtained with a manometer board method. While wet/wet differential pressure sensors have been implemented in previous studies of sediment hydraulic properties (Cartwright et al. 1979; Davis et al. 1991; Harvey et al. 1997), we have not found any previous studies where a wet/wet differential pressure sensor was used to make near-continuous measurements of VHG.

Methods

In this study, monitoring points were installed at a single site along the shore of the Columbia River, near study sites described in previous work (Fritz and Arntzen 2007; Fritz et al. 2007, 2009). The study site consists of unconsolidated sandy gravel sediments underlying an armored cobble river bed surface. Direct measurement of the VHG was accomplished by attaching a wet/wet differential pressure sensor to a minipiezometer (described in following text). The study period was 17 d with a data collection frequency of 5 min. All data loggers were synchronized immediately prior to deployment and clock drift during the test period was negligible.

The minipiezometer is a 15-cm-long (0.8-cm ID) stainless steel screen (Geoprobe®, Salina, KS) attached to a 0.64-cm OD polyethylene tube, which terminates several centimeters above the riverbed surface. For this study, the screen midpoint was installed to a depth of 100 cm below the river bed surface. Installation was accomplished using methods similar to other published methods (Woessner and Sullivan 1984; Welch and Lee 1989; Lee and Harvey 1996; Geist et al. 1998; Baxter et al. 2003; Fritz et al. 2007). A manual post driver was used to pound a disposable drive point and hollow drive rod (Geoprobe) to the desired depth. Once the desired depth was reached, the screen was inserted through the drive rod, threaded onto the tip, and the drive rod was extracted. The minipiezometer was then developed by pumping water until no silt was present in the discharge. Several months passed between minipiezometer installation and attachment of the differential pressure sensor, allowing time for the surrounding formation to settle/collapse around the polyethylene tube and minipiezometer screen. We believe that formation collapse and development of the mini-piezometer resulted in good communication with the aquifer. It was assumed that the depth to the middle of the minipiezometer screen could be accurately measured to be within 2 cm. Error associated with this measurement was primarily attributed to slightly nonvertical drive rod installation and inexact determination of the top of the consolidated substrate on the riverbed. For this installation (100 cm deep), the error associated with the depth measurement was less than 2%.

The differential pressure sensor was a 15 PSID PT2X (Instrumentation Northwest, Kirkland, Washington). The instrument had a range of ±1000 cm water (differential) and a resolution of 0.01 cm water. The stated accuracy of the sensor is ±0.1% of full scale, or 1 cm water. Laboratory validation using an NIST traceable reference (Druck Modular Calibration System, GE Sensing, Billerica, Massachusetts) verified that error in differential pressure measurements using the differential sensor was less than 1 cm water. The sensor is housed in a stainless steel, watertight body 33 cm long, and includes an onboard data logger capable of storing more than 120,000 records at frequencies as high as 10 Hz. The sensor purchased for this study cost approximately $1400. More details on the deployment of this instrument are available in the online supporting information (Figures S1 and S2).

The wet/wet differential pressure sensor method for determining VHG was compared in the field alongside an established method using piezometers and absolute pressure sensors (e.g., Fritz and Arntzen 2007). A piezometer (3.3 cm ID) was installed 1 m away from the mini-piezometer location, at the same river bed surface elevation, with the middle of the screen 116 cm below the river bed. The piezometer has a 46-cm screen interval, so the top of the screen was at the same elevation as the top of the minipiezometer screen. Similar to the minipiezometer, measurement error in the depth to the middle of the piezometer screen was assumed to be less than 2 cm. A river stage gauge consisting of a piezometer screened only in the surface water column was also installed nearby. The elevations of the tops of the piezometer and stage gauge were surveyed using a total station (SET-330R, Sokkia, Olathe, Kansas), with a vertical accuracy of 0.5 cm. The piezometer and stage gauge were outfitted with Solinst LTC Leveloggers™ (Solinst Canada, Georgetown, Ontario). These sensors have a stated accuracy of ±0.5 cm water; the accuracy was verified with the same reference standard as the differential pressure

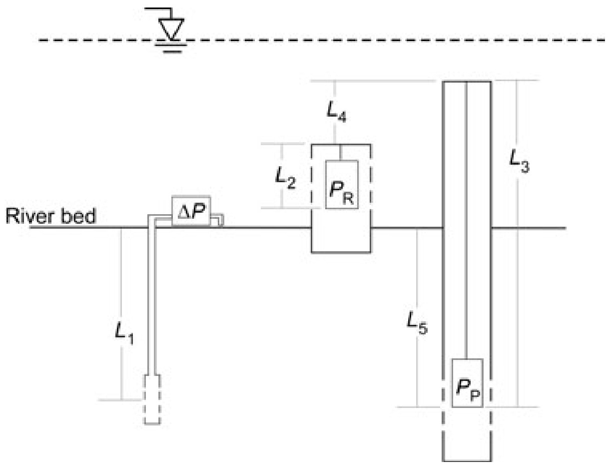

Figure 1. Schematic of setup used to make vertical hydraulic gradient (VHG) measurements using differential pressure and piezometer-based methods.

sensor. The depth to the pressure sensor element of the Leveloggers in both the piezometer and stage gauge were measured with a standard tape, with an estimated accuracy of ±0.5 cm. The total maximum error in the head difference between the surface and the subsurface using the piezometer method described here is 2 cm. This is consistent with previous descriptions of accuracy for this type of method (Hanrahan 2008).

When determining VHG using the wet/wet differential pressure sensor method, only one pressure measurement (ΔP) and one length measurement (L_1) are needed (Figure 1; Equation 1). On the other hand, four length measurements and two pressure measurements are necessary for determining the VHG using the piezometer method (Figure 1; Equation 2). These measurements are head in the piezometer (P_P), head of the river (P_R), distance from the top of the piezometer and stage gauge casing to the sensors (L_2 and L_3), difference in height between the top of the piezometer and stage gauge (L_4), and distance to the center of the piezometer screen (L_5). Here, positive hydraulic gradient is defined as subsurface head being greater than surface water head, resulting in upwelling conditions.

$$VHG_{\mathrm{diff}} = \frac{\Delta P}{L_1} \tag{1}$$

$$VHG_{\mathrm{piezo}} = \frac{(P_P - L_3 + L_4 + L_2) - P_R}{L_5} \tag{2}$$

Results and Discussion

During the study period, the river stage varied between 104.8 and 105.8 m above mean sea level. The VHG measured during the study varied between −0.37 and 0.18 cm/cm (Figure 2). This range of VHG is consistent with measurements made during previous studies in the area (Fritz and Arntzen 2007; Fritz et al. 2007, 2009). The VHG measured by the two methods agreed very well, as demonstrated by several comparison metrics. The maximum difference between the VHG measured by the two methods over any 5-min period was 0.07, or 13% of the difference between the maximum and minimum VHG measured during the study period. Similarly, the root mean square (RMS) error between the two datasets was 0.02.

While the two methods used in this study produced VHG measurements that were very similar, a regression plot revealed two distinct anomalies: the slope of the best-fit linear equation was not equal to one, and the offset was not equal to zero (Figure 3). If the two methods produced exactly equal results, this would not have been the case. The offset between the two methods was likely attributable to errors in length and height measurements in the piezometer method. Indeed, the offset (0.02 cm/cm) equates to a 2 cm error, the same as the estimated error for the piezometer method. The slope not being equal to one was suspected to be an artifact of the different screen lengths used for the two methods.

To test this theory, a simplistic one-dimensional spreadsheet model was used. A 2-m-deep modeling domain with 5-cm vertical intervals was built. Hydraulic conductivity of each cell was assigned based on an exponential equation that fits previous depth discrete hydraulic conductivity measurements (Figure S3; Fritz et al. 2007; Fritz and Arntzen 2007). Darcy flow was then assumed, and various specific discharges were applied across the modeling domain. The VHG across the two screened intervals (differential pressure sensor and piezometer) was then estimated for the range of flow conditions (Table S1). More details on this modeling exercise are provided in the online supporting information (Figure S4). Modeled VHG results were very comparable in relative response to the field measurements (Figure 3). This helped confirm the validity of each method. It also confirmed that the slope of the regression plot was not equal to one as a result of the difference in screen lengths between the piezometer and the differential pressure sensor, as opposed to any fundamental difference in how the sensors were measuring VHG.

This study demonstrates that the new wet/wet differential pressure sensor method of VHG measurement provides results comparable to an instrumented piezometer method. It also reaffirms the reliability of established, less expensive methods of VHG measurement. Since both should be considered as acceptable tools for VHG measurement, it is worth evaluating when each is appropriate. Ideal studies for implementing the wet/wet differential pressure senor for VHG measurement would be cases where VHG will be measured at only a few locations and is known (or suspected) to vary over time. Other situations where this method might be suitable are studies where user-induced measurement error might be expected to contribute a significant amount of uncertainty to the VHG measurement (i.e., small VHG), or where

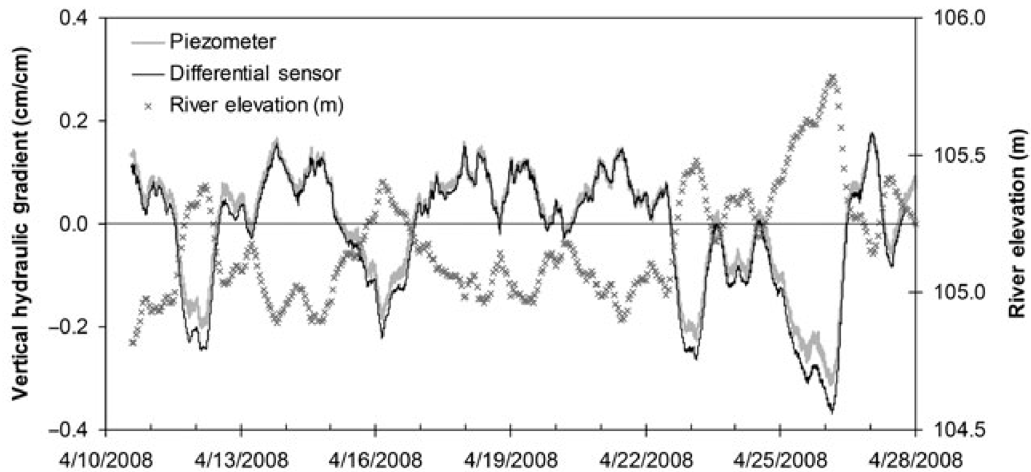

Figure 2. Results of vertical hydraulic gradient (VHG) measurements made during the study period using two methods. River stage also shown for comparison.

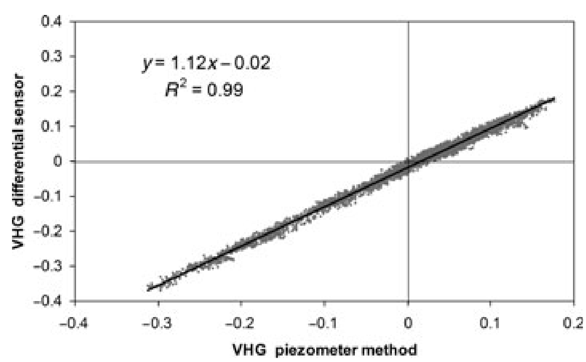

Figure 3. Comparison of vertical hydraulic gradient (VHG) measured and modeled for the piezometer method and the differential pressure method.

field conditions make installation or manual measurements difficult. Examples include studies of VHG in riffle/pool sequences, studies where surface water elevation changes frequently, in deep water settings, and where geologic conditions restrict piezometer installation, but mini-piezometer installation is possible. Also, the small profile of the instrument would make it ideal in settings where vandalism is a concern; it can be easily hidden on the bottom of a river or lake. Because of the higher costs, there are situations where it would not be advantageous to use the wet/wet differential pressure sensor for VHG measurements (e.g., studies of discharge to a lake where changes in VHG are spatially varying, but temporally stable).

Conclusions

Overall, it appeared that for this study the difference between measurement methods was attributable to the accuracy of each method and differences in the equipment setup. There did not appear to be any fundamental difference in the methods; if the instruments could measure the same point in space and time, the results would likely have been nearly identical. The wet/wet differential pressure sensor evaluated in this work proved capable of replicating VHG measurements of a piezometer-based system. The agreement between the two VHG measurement methods was good, indicating that both systems provided an accurate measurement of VHG. The subtle differences between the methods were explainable as a combination of measurement errors resulting in a systematic offset and difference in hardware installation that resulted in a slightly different VHG over a different screened interval. The implications of errors in depth-to-sensor measurements using piezometers highlight one advantage of using the wet/wet differential pressure sensor to measure VHG. While it is possible to minimize errors in head difference when using piezometers, it requires more effort than when using the wet/wet differential pressure sensor. Based on the results of this study, we conclude that the wet/wet differential pressure sensor coupled with a minipiezometer is an acceptable tool for determining VHG.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Sketch of the wet/wet differential pressure sensor and attachment to a minipiezometer.

Figure S2. Example of wet/wet differential pressure sensor deployed in the Columbia River. Picture is with river cobble removed from over top of sensor body.

Figure S3. Hydraulic conductivity of Columbia River sediments at and near the study site.

Figure S4. One-dimensional model built to evaluate impact of screen length on VHG measurements for the two methods. Example shown for specific discharge equal to 0.0002 cm/s.

Table S1. Modeled Vertical Hydraulic Gradient for Differential Pressure Sensor and Piezometer-Based Methods.

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