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Characteristics of high resolution hydraulic head profiles and vertical gradients in fractured sedimentary rocks

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SUMMARY

Accurately identifying the position of vertical hydraulic conductivity (K_v) contrasts is critical to the delineation of hydrogeologic units that serve as the basis for conceptual and numerical models of groundwater flow. High resolution head profiles have identified the position and thickness of K_v contrasts in clayey aquitards but this potential has not yet been thoroughly evaluated in sedimentary rocks. This paper describes an experiment in which head profiles with the highest, technically feasible resolution were obtained using Westbay® multilevel systems (MLS) installed in 15 cored holes at three sedimentary rock research sites with contrasting geologic and flow system conditions. MLSs were installed to maximum depths between 90 and 260 m with 2–5 monitoring zones per 10 m. Head profiles were measured over multiyear periods. The vertical component of hydraulic gradient (i.e., vertical gradient) was calculated for each pair of adjacent monitoring intervals in every MLS and then categorized based on its repeatability to facilitate interpretation of K_v contrasts and comparisons within boreholes, between boreholes at the same site, and between sites. The head and vertical gradient profiles from all three sites display systematic (i.e., simple, geometric) shapes defined by repeatable intervals of no to minimal vertical gradient, indicating relatively high K_v units, bounded by shorter depth intervals with large (up to −50 m/m) vertical gradients, indicating relatively low K_v units. The systematic nature of the profiles suggests flow in regular and interconnected fracture networks rather than dominated by a few key fractures with irregular orientations. The low K_v units were typically thin, with their positions and thicknesses not predicted by lithostratigraphy or detailed lithologic, geophysical, and horizontal hydraulic conductivity data. Hence, the position and thickness of units with contrasting K_v would not be evident if MLSs with the conventional number of monitoring zones had been used. Furthermore, the detailed profiles can be strongly diagnostic of hydrogeologic unit boundaries or layers and can be used to improve the quantitative assessment of flow system conditions that is foundational to understanding contaminant plume migration.

1. Introduction

One-dimensional vertical profiles (e.g., geological, geophysical, geochemical, hydraulic conductivity) have been a fundamental tool in the characterization of contaminated groundwater systems since at least 1960 (e.g., Parsons, 1960). Hydraulic head is fundamental to all groundwater investigations, yet examples of measured head profiles in the literature are limited. Most published examples are from shallow, unconsolidated deposits and were obtained to assess the integrity of clay aquitards in the context of waste isolation and protection of underlying aquifers (e.g., Desaulniers and Cherry, 1989; Desaulniers et al., 1981; Goodall and Quigley, 1977; Husain et al., 1998; Keller et al., 1989; O'Shaughnessy and Garga, 1994; Parker et al., 2004; Ruland et al., 1991). These studies were most concerned with vertical transport of contaminants in the upper 50 m of the subsurface and relied heavily on vertical profiles with many (~10–15) depth-discrete data points for stable and radioactive isotopes, natural solutes, fracture observations, and head. In general, these studies used head profiles to calculate the vertical component of hydraulic gradient (i.e., vertical gradient), which is needed to simulate advective–diffusive transport of various contaminants or chemical tracers. Several studies also used head profiles to characterize the position and thickness of hydraulic conductivity contrasts due to changes in the properties of the fracture networks in clayey aquitards (e.g., Desaulniers and Cherry, 1989; Keller et al., 1989; O'Shaughnessy and Garga, 1994). Increases in the vertical gradient and decreases in the temporal variability of hydraulic head with depth were attributed to decreases in the frequency of

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hydraulically active fractures. Identifying the depth of hydraulically active fractures using head profiles was also demonstrated using a discrete fracture network numerical model (Harrison et al., 1992).

Although detailed and depth-discrete (i.e., high resolution) head profiles are a useful characterization tool in fractured clayey materials, they are not commonly utilized in investigations of other fractured geologic media at relatively shallow (<300 m) depths. Several investigations have collected and analyzed head profiles to improve understanding of contaminant transport and fate in a variety of fractured rock environments (e.g., Fisher and Twining, 2011; Novakowski and Lapcevic, 1988; Perrin et al., 2011; Raven et al., 1990; Taylor et al., 2003; Twining and Fisher, 2012) or to understand groundwater surface water interactions in bedrock settings (e.g., Oxtobee and Novakowski, 2002; Praamsma et al., 2009). Head profiles have also been used in research focused on hydraulics, such as to identify transient flow conditions in a shale aquitard and characterize its impact on the flow system (Eaton et al., 2007; Eaton and Bradbury, 2003) as well as to characterize the hydraulic connectivity of fractures observed in a single borehole penetrating a siliciclastic aquifer (Gellasch et al., 2012), examine the extent of a perched aquifer system in layered sandstones and dolostones (Carter et al., 2011), and evaluate the permeability of a fault in a sandstone/mudstone system in Texas (Zhurina, 2003).

The head profiles presented in these studies were not explicitly used to delineate contrasts in hydraulic conductivity associated with distinct hydrogeologic (or hydrostratigraphic) units. The term hydrogeologic unit is used here to represent partitions of the groundwater flow domain with contrasting hydraulic conductivities at a specified scale (modified slightly from Meyer et al., 2008). Accurate three-dimensional (3D) delineation and characterization of hydrogeologic units (HGUs) is critical because they form the basis for conceptual and numerical models of groundwater flow and contaminant transport and ultimately control the trajectory of groundwater flow paths and travel times in these models. In layered, fractured sedimentary systems, where anisotropy is expected to be large, identification of contrasts in bulk vertical hydraulic conductivity (K_v) with depth is important for HGU delineation. Application of high resolution head profiles to identify the position and thickness of these K_v contrasts is founded in flow system theory, has been proposed by others (Bradbury et al., 2006; Cherry et al., 2006; Hart et al., 2008; Meyer et al., 2008), and is a logical extension from work done in fractured, clay aquitards.

Meyer et al. (2008) presented the first experiment in which a high resolution head profile was used as the primary evidence for delineation of HGUs for a single borehole in fractured sedimentary rock at a site in Wisconsin. The head profile included 36 measurements over 121 m of open borehole (i.e., 3 monitoring zones per 10 m) with 27% of the open borehole length sealed. The high resolution head profile displayed depth intervals of nearly uniform head separated by nine prominent inflections where large head changes occurred over much smaller depth intervals, referred to here as a systematic (i.e., simple, geometric) shape. Their work focused on the prominent inflections, and interpreted them as a relative increase in the resistance to vertical flow. Furthermore, they proposed that seven of the nine inflections were related to reduced vertical connectivity between adjacent fracture networks rather than relatively low permeability intervals with measurable thickness.

Meyer et al. (2008) did not rigorously evaluate depth intervals with nearly uniform head and measurement reproducibility, yet these are key items that need to be addressed before head profiles can be used in a 3D context to delineate contrasts in hydraulic conductivity and HGUs. The general utility of high resolution head profiles in sedimentary rock systems was not evaluated as their study was limited to one high resolution head profile at a single field site. Moreover, the systematic shape of Meyer et al.'s head profile suggested flow occurring in networks of regular and strongly interconnected fractures rather than flow controlled by a few key fractures with irregular orientations (Chernyshev and Dearman, 1991), two scenarios that broadly represent two end member conceptual models for flow in fractured rocks (Berkowitz, 2002). Thus it was of interest to determine if the systematic shape of the head profile presented by Meyer et al. (2008) is a consequence of the specific geology at the Wisconsin site or a more general characteristic of sedimentary rock flow systems.

The objectives of this study were therefore to develop a robust method for collection and quantitative spatial and temporal evaluation of head profiles in preparation for use in interpretation of K_v contrasts and hydrogeologic units in 3-D, test the method in a variety of sedimentary rock types and flow system conditions, and add the detailed head profile data sets to the very small number available in the literature.

The objectives were addressed by collection of repeated high resolution head profile measurements from 12 locations at three field sites with contrasting sedimentary rock types and flow system conditions. The data collected were used to develop an approach for qualitatively evaluating the head profiles for eventual use in delineating vertical hydraulic conductivity contrasts and HGUs in a 3D context.

2. Conceptual model

The use of high resolution head profiles to identify contrasts in K_v and delineate HGUs is founded in flow system theory. The steady-state distribution of head is a function of the length to depth ratio of the groundwater basin, the water table configuration, and subsurface variations in hydraulic conductivity (Freeze and Witherspoon, 1967; Tóth, 1963). Distinct variations in subsurface hydraulic conductivity are conceptualized as units (HGUs) with definable 3D geometries. Traditionally, evaluation of flow systems relies on plots of equipotential and flow lines in 2D vertical cross-sections forming a flow net. Freeze and Witherspoon (1967) show numerically that contrasts in vertical and horizontal hydraulic conductivity of HGUs results in refraction of the flow and equipotential lines at the boundaries between these units (Fig. 1a). Therefore, if head data are collected from many, depth-discrete points along a vertical profile at a position in the regional flow system where at least some vertical flow exists, the position and thickness of HGUs with contrasts in K_v will be indicated by a change in the vertical gradient (Fig. 1b). The premise of using hydraulic head profiles to identify contrasts in K_v in fractured sedimentary rocks relies on three key assumptions: (1) the fracture network for each HGU is sufficiently dense (i.e., high fracture frequency or intensity) and interconnected to behave as an equivalent porous medium with uniform bulk hydraulic properties, (2) head measurements are sufficiently depth-discrete to avoid blending across units with contrasting K_v and are measured in enough detail to resolve changes in head due to thin K_v contrasts from the regional vertical gradient, and (3) conditions at the time of head profile measurement are at or near steady-state such that uniform vertical gradients exist across the full thickness of each HGU with contrasting K_v. Application of the method to three field sites with different geologic and hydrogeologic characteristics allows for preliminary evaluation of these assumptions.

3. Methods

3.1. Description of field sites

The three contaminated, sedimentary rock field sites selected are a subset of sites from a field-based research program