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Multiple-scale hydraulic characterization of a surficial clayey aquitard overlying a regional aquifer in Louisiana

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A B S T R A C T

The vertical hydraulic conductivity (K_v) of a 30-m thick surficial clayey aquitard overlying a regional aquifer at an industrial site in the Mississippi River Valley in Louisiana was investigated via intensive hydraulic characterization using high resolution vertical hydraulic head profiles with temporal monitoring and laboratory tests. A study area was instrumented with a semi-circular array of piezometers at many depths in the aquitard at equal distance from a large capacity pumping well including replicate piezometers. Profiles showed negligible head differential to 20 m bgs, below which there was an abrupt change in vertical gradients over the lower 8–10 m of the aquitard. Hydraulic characteristics are strongly associated with depositional environment; the upper zone of minimal head differentials with depth and minimal variation over time correlates with Paleo-Mississippi River backswamp deposits, while the lower zone with large head differentials and slow but moderate head changes correlates with lacustrine deposits. The lower zone restricts groundwater flow between the surface and underlying regional aquifer, which is hydraulically connected to the Mississippi River. Lab tests on lacustrine samples show low K_v (8×10^{-11}–4×10^{-9} m/s) bracketing field estimates (6×10^{-10} m/s) from 1-D model fits to piezometric data in response to large aquifer head changes. The slow response indicates absence of through-going open fractures in the lacustrine unit, consistent with geotechnical properties (high plasticity, normal consolidation), suggesting high integrity that protects the underlying aquifer from surficial contamination. The lack of vertical gradients in the overlying backswamp unit indicates abundant secondary permeability features (e.g. fractures, rootholes) consistent with depositional and weathering conditions. 2-D stylized transient flow simulations including both units supports this interpretation. Other published reports on surficial aquitards in the Gulf Coast Region pertain to Pleistocene deposits that lack laterally extensive lacustrine units and where K_v is enhanced by secondary permeability features, resulting in clayey aquitards with poor integrity.

1. Introduction

Many potable water aquifers are overlain by surficial clayey aquitards governing groundwater recharge and providing some degree of protection from near surface sources of contamination. However, the literature provides few comprehensive investigations of the magnitude and nature of vertical hydraulic conductivity (K_v) of surficial aquitards. Two general categories of hydraulic methods are used to determine K_v: laboratory measurements on core samples and field hydraulic tests, where an overlying or underlying aquifer is pumped with pore-pressure monitoring of response in the aquitard. In-depth reviews of field methods are provided by Neuzil (1986), van der Kamp (2001), Cherry et al. (2006), and Batlle-Aguilar et al. (2016). Williams and Farvolden (1967) were the first to report on aquitard K_v based on piezometer time series hydraulic head monitoring in a clayey glacial till in Illinois, and concluded that the rapid piezometer responses required the aquitard to have hydraulically active vertical fractures. Wolff (1970) describes a field study where a surficial aquifer was pumped and piezometers in the underlying clayey aquitard responded very slowly over many weeks. This slow response was accounted for quantitatively using an analytical 1-D transient flow model with input values for hydraulic diffusivity that matched well with independent laboratory tests on undisturbed core samples, suggesting a lack of secondary pathways such as fractures. Grisak and Cherry (1975) provide a much different result in an aquifer pumping test with monitoring of piezometers in an overlying surficial clayey aquitard at a waste disposal site in Manitoba, where rapid and strong response in some of the aquitard piezometers to

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the aquifer drawdown suggested the presence of through-going fractures. However, some of the aquitard piezometers did not respond over the 30-day period of the test, likely because these piezometer screens were not as proximate to widely spaced features such as fractures or other preferential pathways. In such a scenario, it only takes rapid response in one piezometer to indicate the presence of through-going fractures. The lab-derived K_v values from oedometer tests were about two orders of magnitude lower than the field bulk K_v derived from numerical modeling of piezometer responses to pumping, with the difference attributed to presence of vertical fractures. Davis (1972) describes use of natural hydraulic transients to study hydraulic diffusivity of aquitards including propagation of response across low permeability units from monitoring aquifers above and below the aquitard. Keller et al. (1989) compare field-scale measurements of K_v derived from analysis of downward propagation of seasonal water table fluctuations in an oxidized clayey till into an underlying unoxidized till via piezometric monitoring with field slug tests, and laboratory consolidation and permeameter tests at a site in Saskatchewan. They found that the field-scale results compared well with those from the small-scale laboratory tests and attributed this to lack of fractures in the unoxidized till. Döll and Schneider (1995) applied several field methods, including slug tests, pumping tests of an underlying aquifer with aquitard monitoring, and tidal propagation from the aquifer into the aquitard, and noted larger scale field tests generally provided larger K_v values than laboratory permeameter tests, but at this site did not indicate the influence of secondary permeability features such as fractures. The studies reported above and others show that comparison of small-scale laboratory tests on core samples with larger-scale field values derived from piezometer response to pumping tests or natural transients can provide some evidence for the presence or absence of secondary pathways or other types of heterogeneity relevant to the effective field-scale K_v for clayey aquitards. However, they also highlight the difficulty in conclusively showing a lack of fractures and other preferential pathways, as well as the need for multiple lines of evidence.

This paper concerns investigations of K_v of a surficial clayey aquitard in the Mississippi River Valley near Baton Rouge, Louisiana, at a chemical manufacturing facility overlying a regional sand-gravel aquifer used for water supply. Parts of the Gulf Coast region have surficial aquitards overlying aquifers and the literature specific to hydrogeologic studies of these aquitards is limited to those of Pleistocene origin (e.g., Hanor, 1993, 1995; Cramer, 1988; PPG, 1995); such studies indicate the major influence of secondary permeability features such as fractures, rootholes or burrows, or stratigraphic windows. Based on evidence from Pleistocene deposits, Cramer (1988) indicates the presence of secondary pathways should be taken as the expected condition of surficial aquitards in Louisiana. However, surficial aquitards in the Mississippi River Valley are comprised of Holocene deposits; therefore, this generalization may not be applicable because of differences in depositional origins and post-depositional influences between Pleistocene and Holocene deposits (Kesel, 2008). A unique approach was taken to investigate the hydraulic conductivity of the aquitard at the study site. The Mississippi River channel eroded through the entire ~30 m thickness of the aquitard and therefore the hydraulic connection laterally is rapid and direct from the river outward to the aquifer domain everywhere beneath the site. Robust determination of aquitard K_v was enhanced by this hydraulic connection, where large (>7 m) seasonal changes of river levels cause nearly as large a variation in hydraulic head at the base of the aquitard, providing the opportunity to monitor propagation of this cyclical pressure pulse upward into the aquitard. The goal was to determine whether or not fractures or other preferential pathways occur in the basal part of the aquitard and influence vertical flow. A semi-circular array of piezometers at various depths was installed across the aquitard at a location on the facility, referred to as the detailed study site or DSS (Fig. 1) for long-term monitoring of pressure response due to river stage variation, along with a shorter pressure pulse imposed by an aquifer pumping test. Laboratory consolidation and permeameter tests were conducted on core samples to evaluate small-scale K_v at various depths for comparison to field-derived values.

2. Study site and geological setting

The study site is a large (~750 ha) chemical manufacturing facility that has been in operation since the early 1950s near Plaquemine, Louisiana, situated next to the Mississippi River. Drainage canals throughout the site control hydraulic head in the surficial part of the aquitard. The selection of the study site for this comprehensive assessment of the magnitude and nature of the hydraulic conductivity of a Holocene aquitard was guided by a previous study of this area by Kesel (2008), who reported on the age and depositional environments of the sediment layers comprising the aquitard. Fig. 1a shows the overall site area and proximity to the Mississippi River (inset shows the DSS) and Fig. 1b shows a schematic cross-section from the river through the DSS. Fig. 2 shows the hydrogeologic setting and stratigraphy of the regional surficial aquitard (known as the top stratum; Whiteman, 1972) that overlies the upper Pleistocene aquifer. Kesel (2008) examined cores and obtained numerous carbon-14 dates to determine the deposition times and rates of the top stratum at the study site. These studies show the aquitard has two main parts: 1) an upper unit comprised primarily of overbank and backswamp deposits associated with the ancestral Mississippi River, and 2) a lower unit comprised of lacustrine deposits in lakes formed of flood waters from the ancestral Mississippi River. Both types of deposits are widespread components of the aquitard in the Lower Mississippi River Valley (Krinitzsky and Smith, 1969) but field-scale information on hydraulic conductivity of these units is lacking. In addition to detailed geologic information, abundant information is available from geotechnical studies conducted for facility development, providing a framework for extrapolation of findings from this site to other areas in the Mississippi River Valley with similar deposits. The impetus for the current hydraulic study was the need to assess the potential for contaminant migration through the aquitard.

3. Methods

3.1. Core collection and laboratory tests

Continuous cores were collected at two locations at the DSS using two methods: 1) sonic techniques were used in February 2003 to collect cores for stratigraphic characterization and installation of a 1.5-m long well screened in the upper portion of the Upper Plaquemine aquifer (PZ-60) and 2) mud-rotary techniques were employed in February 2005 with continuous sampling using 7.6 cm diameter thin-walled Shelby tubes advanced ahead of the mud-rotary casing (borehole designated as LAOB-23). These Shelby samples (Table 1) were collected continuously in 0.61 m runs from 15.8 to 29.2 m bgs spanning the lower unit (22 samples total). The ends were sealed with wax for moisture preservation in the field and the samples were shipped on ice to a geotechnical testing lab where they were stored in a cold room prior to testing. These cores were extruded in early 2008, during which time the cores were examined in detail, photographed, and subsamples collected for various measurements, including moisture content (ASTM D2216-98), specific gravity (ASTM D854-02), particle size distribution via hydrometer analysis (ASTM D422-63), total organic carbon content (Walkley-Black wet oxidation method), wet and dry unit