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Determining In Situ Properties of Claystone Aquitards Using Pore Pressure Responses from Grouted-in Pressure Transducers

Laura A. Smith, S. Lee Barbour, M. Jim Hendry

University of Saskatchewan, Saskatoon, Saskatchewan

Summary

Traditional methods to determine hydraulic conductivity (K) of claystone aquitards generally consist of conducting laboratory tests on core samples. However, core samples of heavily overconsolidated or indurated clay shales are often disturbed during the sampling process and consequently, laboratory measured properties may not be representative of *in situ* conditions. Here, we present a method to determine the *in situ* K of a thick claystone aquitard using pore pressure data from multiple grouted in pressure transducers. Ten vibrating wire pressure transducers were installed at depths between 25 and 325 m BG and placed directly within the cement-bentonite grout annulus. Pore pressure was recorded every 30 minutes from installation (grouting) to stabilization. Using early time data, the pore pressure recovery was simulated using a numerical modeling program incorporating the compressibility and porosity data obtained previously for the grout and formation (Smith et al., 2013).

Introduction

Aquitards are geologic deposits of low hydraulic conductivity ($K \leq 10^{-8}$ m s^{-1}) that limit ground water flow and contaminant transport to adjacent aquifers. Low K shales with a high clay content (claystone aquitards) can act as caprock formations, trapping or concentrating oil, gas or water, and preventing it from migrating into overlying shallow aquifers or to discharge areas. The design of *in situ* methods for the recovery of petroleum products (e.g. Steam-Assisted Gravity Drainage and Cyclic Steam Stimulation) rely on characterization of the caprock properties to evaluate caprock integrity. The ability to manage and protect ground water resources also requires that the hydrogeologic properties of aquitard formations be well defined (van der Kamp, 2001). Formation properties (K; vertical compressibility, α; and specific storage, Ss) of claystone aquitards are traditionally determined using laboratory tests; however, core samples removed from the subsurface may not yield results representative of *in situ* conditions. An alternative *in situ* method using grouted-in pressure transducers to estimate *in situ* K is presented in this paper.

Method

A rotary drill rig was used to continuously core through 325 m of Cretaceous claystone in Southern Saskatchewan. Ten vibrating wire pressure transducers (Geokon; model 4500S) were installed in the borehole by fixing them to the outside of a steel grout pipe and lowering it into the borehole. A 4% bentonite/96% cement grout with an approximate specific gravity of 1.7 was pumped down the pipe until there was grout return to surface. Immediately after placement, the transducers were connected to a datalogger and programmed to measure pressure and temperature every 30 minutes. A barometer (Solinst, 2001 LT) installed at ground surface was used to measure barometric changes every 30 minutes at the same time stamp as the pressure transducers.

Prior to grouting, the pore pressure is negligible because the transducers are situated in an empty borehole. During grouting, the pore pressure in the borehole increases rapidly until there is grout return at surface. When the grout begins to cure, free water in the system is consumed during the chemical processes causing the pore pressure to decrease and the temperature to increase (heat of hydration). Once fully cured, the pore pressure stops decreasing and the temperature stabilizes. Water begins to move into the grout annulus causing the pore pressure to gradually increase until it is at equilibrium with the adjacent formation, generating a porewater recovery curve (Figure 1). Theoretically, this rate of recovery is dependent on the hydraulic properties of the formation and the grout annulus (Smerdon, 2014).

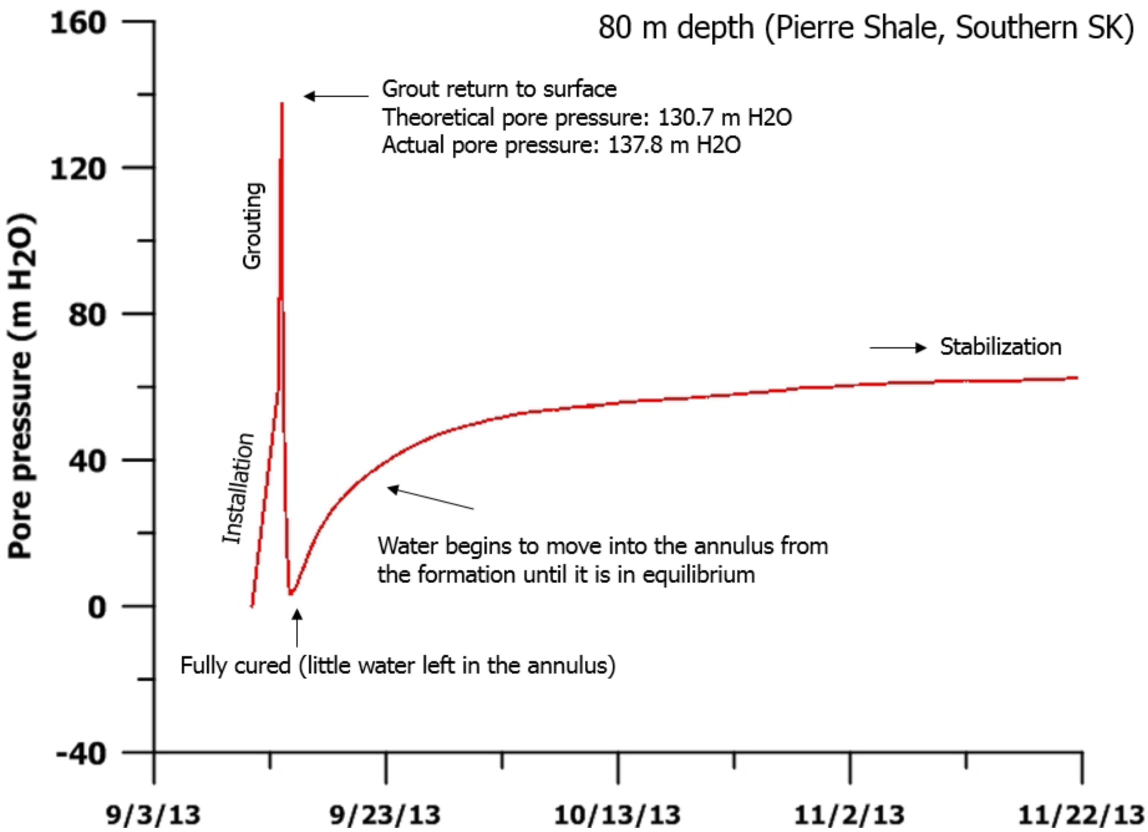

Figure 1: Typical pore pressure response after grouting in a pressure transducer.

In situ K was estimated from the transducer data by simulating the early time pore-pressure measurements following setting of the grout, using a 1D axisymmetric, finite element, numerical model (SEEP/W, GEO-SLOPE International Ltd., 2007). The model simulated the recovery of pore pressure in the grouted borehole (100 mm radius) with the pore pressure in the adjacent aquitard (50 m radius) over 365 days. The initial pressure within the grout was defined by the measured pore-pressure following setting of the grout (100 mm radius). The initial head in the formation was defined from the equilibrium pressure following recovery. In addition to K, the rate of pore pressure recovery is dependent on the porosity (n) and the coefficient of volume change (m_v) of both the grout and the formation. The n and m_v values for the grout and the n value for the aquitard were established from laboratory measurements. The m_v values for the formation were measured in situ based on observed pore pressure fluctuations in response to barometric fluctuations (Smith et al., 2013). Using these parameters, K was varied systematically until an optimum visual fit to the transducer data was achieved (Figure 2).

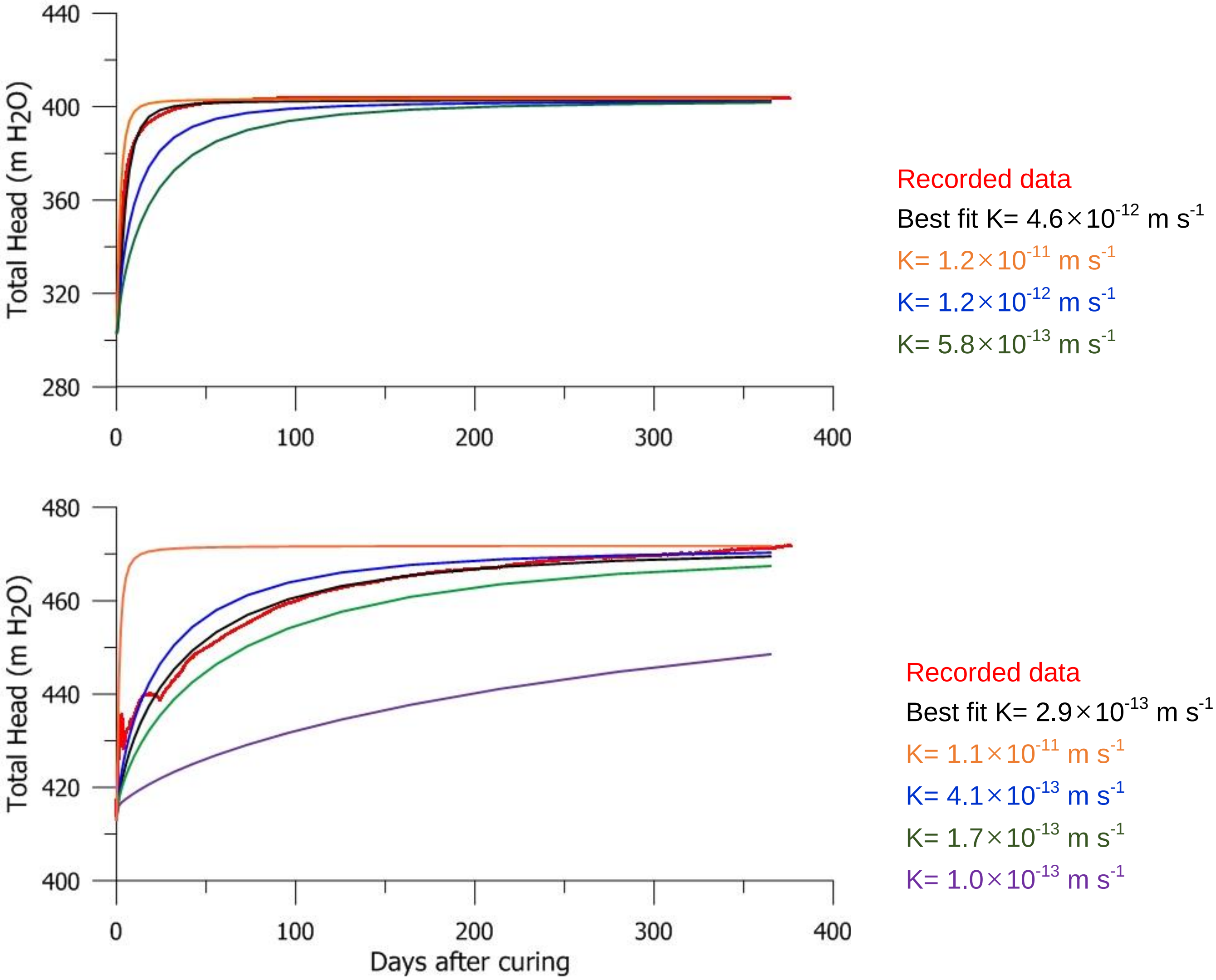

Figure 2: Measured and simulated total hydraulic head recovery for two transducers (B and E). Transducer B illustrates the characteristic recovery trend of the deep transducers (225-325 m BG) and Transducer E illustrates the characteristic recovery trend of the shallow transducers (50-185 m BG).

Results

The ten installed transducers were grouped into 3 separate groups based on similar patterns of pore-pressure recovery: the near surface transducer (25 m), the shallow transducers in the Pierre Shale (50-185 m BG), and the deep transducers in the 1st and 2nd Speckled Shale and Belle Fourche Formations (225-325) (Figure 3). The near surface transducer recovered too quickly to be modeled. The shallow transducers in the Pierre Shale recovered to equilibrium pressures over about 250 days while the deeper transducers reached equilibrium within 50-75 days (Figure 2). The resulting *in situ* K estimates illustrate a general increase in K with depth, which is likely due to varying lithology of the formations and/or the presence of fracturing in the 1st and 2nd Speckled Shale and Belle Fourche Formations (Figure 3). The results of triaxial laboratory testing of core samples were generally greater than the *in situ* K by up to one order of magnitude in the Pierre Shale, and less than the *in situ* K in the Colorado Shales (1st and 2nd Speckled Shale).

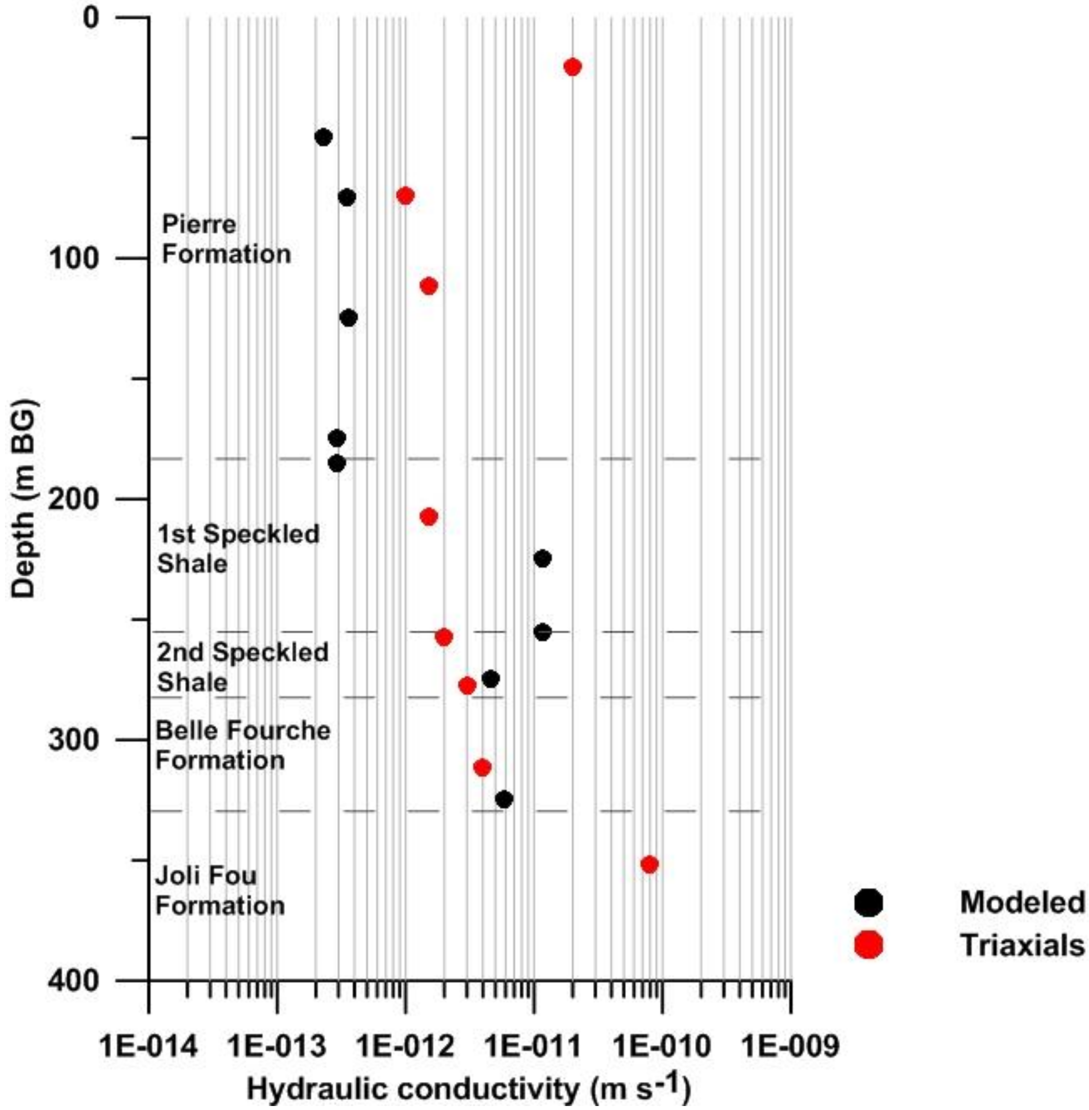

Figure 3: A comparison of laboratory and *in situ* results for estimated K.

Conclusions

This study demonstrates how using sensitive pressure transducers in deep boreholes can provide *in situ* estimates of K in thick aquitards. Using previously determined hydraulic properties of the aquitard the pore pressure recovery from installation to equilibrium with the pore pressure in the adjacent aquitard can be simulated by varying the K until a good fit is achieved. The resulting K provides an *in situ* estimate for the aquitard at the location of each installed transducer which can then be compared to laboratory results. Current work is focused on determining an overall K through the aquitard using numerical modeling based on the current stabilized head profile, geologic properties, assumed initial conditions, and a transient drawdown due to mine dewatering in the underlying aquifer formation.

Acknowledgements

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