GeoConvention 2014 FOCUS
adapt refine sustain

A New Technique for Determining In Situ Parameters of Argillaceous Deposits using Pore Pressure Responses

Laura A Smith, M J Hendry, G van der Kamp
University of Saskatchewan, Saskatchewan, Canada

Summary

Laboratory consolidation tests are typically used to determine formation properties (vertical compressibility, α; specific storage, S_S; and vertical hydraulic conductivity, K_v) of claystone aquitards. However, when core samples are removed from the subsurface and re-equilibrate at surface pressure, the geotechnical properties of the sample may not be representative of in situ conditions. Here, we present a method to determine the in situ α and S_S of a thick sequence of Cretaceous aged claystone by estimating the loading efficiency (γ) of a formation from pore pressure responses to barometric pressure fluctuations. Ten vibrating wire pressure transducers were installed at depths varying between 25 and 325 m BG in a thick claystone aquitard and placed directly within the cement-bentonite grout annulus. In the pore pressure records, barometric pressure changes, earth tides, and precipitation events can be clearly identified with a resolution equivalent to millimeter of hydraulic head. Analyzing the pore pressure response to known barometric fluctuation resulted in the calculation of γ (0.6-0.93), α (2.5×10^{-7} to 2.2×10^{-6} kPa^{-1}), and S_S (2.6×10^{-5} to $4.5 \times 10 \times 6$ m^{-1}), all of which decrease with depth. Laboratory analysis of core samples from the borehole provided estimates of α and Ss which were as much as an order of magnitude greater than the in situ estimates. The findings suggest that the fully grouted transducer method can provide an accurate and reliable means to monitor pore pressure changes in deep aquitard systems, better define in situ parameters for overconsolidated argillaceous deposits and help characterize caprock integrity.

Introduction

Aquitards are geologic deposits with low hydraulic conductivity ($K \leq 10^{-8}$ m s^{-1}) and sufficient regional extent, thickness and competency to impede groundwater flow between or to aquifers (Cherry and Parker, 2004). In addition to the ability to control recharge and contaminant transport to adjacent aquifers, aquitards can act as isolating units to protect shallow groundwater from contamination by fluids and gases injected into deeper formations. More recently, clay-rich aquitards are being considered as host formations for sequestration of hazardous wastes. The ability to manage and protect groundwater resources can be dependent on accurate determinations of the hydrogeologic properties of a formation (α, Ss, S, K_v) (van der Kamp, 2001). Researchers have previously relied on laboratory consolidation tests to determine these properties of low K material (Neuman and Witherspoon, 1972; Keller et al., 1986, 1989; Shaver, 1997). However, these laboratory based results may not be representative of in situ conditions. Core samples undergo unavoidable stress changes during collection causing the material to re-equilibrate at surface pressure and can increase the α of the material (Klohn, 1965; Radhakrishna and Klym, 1974). Subsequent analyses from the laboratory determined α may lead to estimates of Ss or K_v that can be orders of magnitude greater than in situ conditions (Grisak and Cherry, 1975; van der Kamp and Schmidt, 1997; van der Kamp, 2001). Here, we present a field method using sensitive pressure transducers coupled with electronic dataloggers to determine the in situ elastic properties of a formation by monitoring the pore pressure responses to surface loading. This method may also be utilized as a tool to monitor and define caprock integrity of SAGD deposits.

Theory

When a surface load is applied to a saturated profile, the stress is shared by the porewater and the soil structure of a formation. The applied pressure will produce an instantaneous change in porewater pressure at depth (Terzaghi and Frohlich, 1936; Jacob, 1940; Skempton, 1954). Effective stress (σ') is the difference between the total stress and the pore pressure (Terzaghi, 1923):

$$\sigma = \sigma' + p, \qquad (1)$$

where σ is the total stress ($MT^{-2}L^{-1}$) and p is the pore pressure ($MT^{-2}L^{-1}$).

The same principle can be applied to atmospheric loading, in which barometric pressure is transmitted through the underlying formation and the stress will be shared by the porewater and the soil structure (Terzaghi, 1923; Anochikwa et al., 2010). In a laterally homogenous formation, the stress acting on the underlying aquitard will be exhibited as vertical stress and equal to the atmospheric pressure at ground surface (van der Kamp and Gale, 1983).

Skempton's B-bar coefficient (B) or loading efficiency (LE;γ) (Skempton, 1954; Wang, 2000) is the ratio of the pore pressure response to an applied load. If the porewater is much less compressible than the formation, as is the case with many clay rich aquitards, the porewater will instantaneously bear the full loading pressure, resulting in a γ of 1. However, in stiff, overconsolidated formations with low α, the soil skeleton of the formation will bear some of the applied load and the γ will decrease well below 1, providing a means to estimate the α of the formation (Bishop, 1973; van der Kamp and Gale, 1983; Terzaghi, 1996; Anochikwa, 2010). While the degree of saturation and porosity can influence the γ of a formation, in very stiff overconsolidated formations, the primary factor controlling LE is the α of the formation (Skempton, 1954; van der Kamp and Gale, 1983; Anochikwa, 2010):

$$\alpha = \frac{\gamma\, n\beta}{1-\gamma}, \qquad (2)$$

where β is the compressibility of water (4.6×10^{-7} kPa^{-1}). Specific storage for a saturated, compressible porous media can be calculated using:

$$S_s = \rho g(n\beta + \alpha), \qquad (3)$$

where ρg is the specific gravity of water (9.8 kN m^{-3}).

Method

A rotary drill rig was used to continuously core through 325 m of Cretaceous claystone in Southern Saskatchewan. Samples were collected and preserved in the field, then transported to the University of Saskatchewan for various analyses. 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% benonite / 96% cement grout mixture with an approximate specific gravity of 1.69 was pumped down the pipe until there was grout return at surface. Once in place, the transducers were connected to an automated data acquisition system (Argus Monitoring Software, Version: 2.6.0.1) and programmed to measure pressure and temperature every 30 minutes. A barometer (Solinst, 2001 LT) was installed at ground surface above the borehole to measure barometric changes every 30 minutes at the same time stamp as the pressure transducers.

Once the transducers came to a relatively steady state, the pore pressure responses to barometric changes provided a means to assess how much the pore pressure varied with a known applied load. If the entire applied pressure is borne by the porewater in the formation (γ =1), then a barometric change of 0.1 m should result in a pore pressure response of 0.1 m. The loading efficiency at the location of each transducer was determined by systematically multiplying the change in barometric pressure ($B-B_{ave}$) by a number between 0 and 1.0 (representing γ) and subtracted from the raw porewater pressure data (Equation 4). This process produced a series of trends which were then superimposed on one another to visually determine the trend with the 'straightest' increases and decreases between precipitation events (Figure 1).

$$p* = [p_t - B_{ave}] - \gamma\,(B - B_{ave})\,, \qquad (4)$$

where p* is the corrected porewater pressure, and p_t is the uncorrected absolute pore pressure, B is the barometric pressure, and B_{ave} is the average barometric pressure.

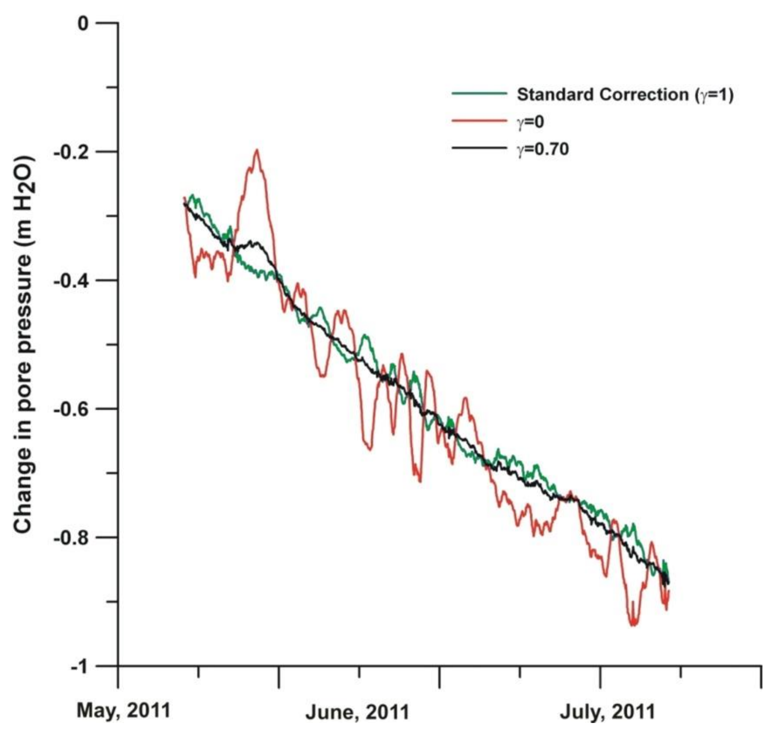

Figure 1. Comparison of no correction (γ=0), standard correction (γ=1), and the visual best fit (γ=0.70) for transducer A (325m BG). Data presented as change in pore pressure relative to average pore pressure (from Smith et al., 2013).

Results

Values for γ, α, and Ss were determined from the pore pressure responses to barometric pressure changes for all ten transducers using the method described above (Figure 2). The results indicate that loading efficiencies decrease with depth and suggests that the formation becomes increasingly less compressible with increasing depth. Using the estimated LE, α and Ss were calculated using Equations 2 and 3 and were also found to decrease with depth. The results of laboratory 1D consolidation (oedometer) tests of nine core samples are also plotted on Figure 2 (B). In all cases, the laboratory consolidation tests overestimate the compressibility of the sample, which lead to an overestimation of Ss.

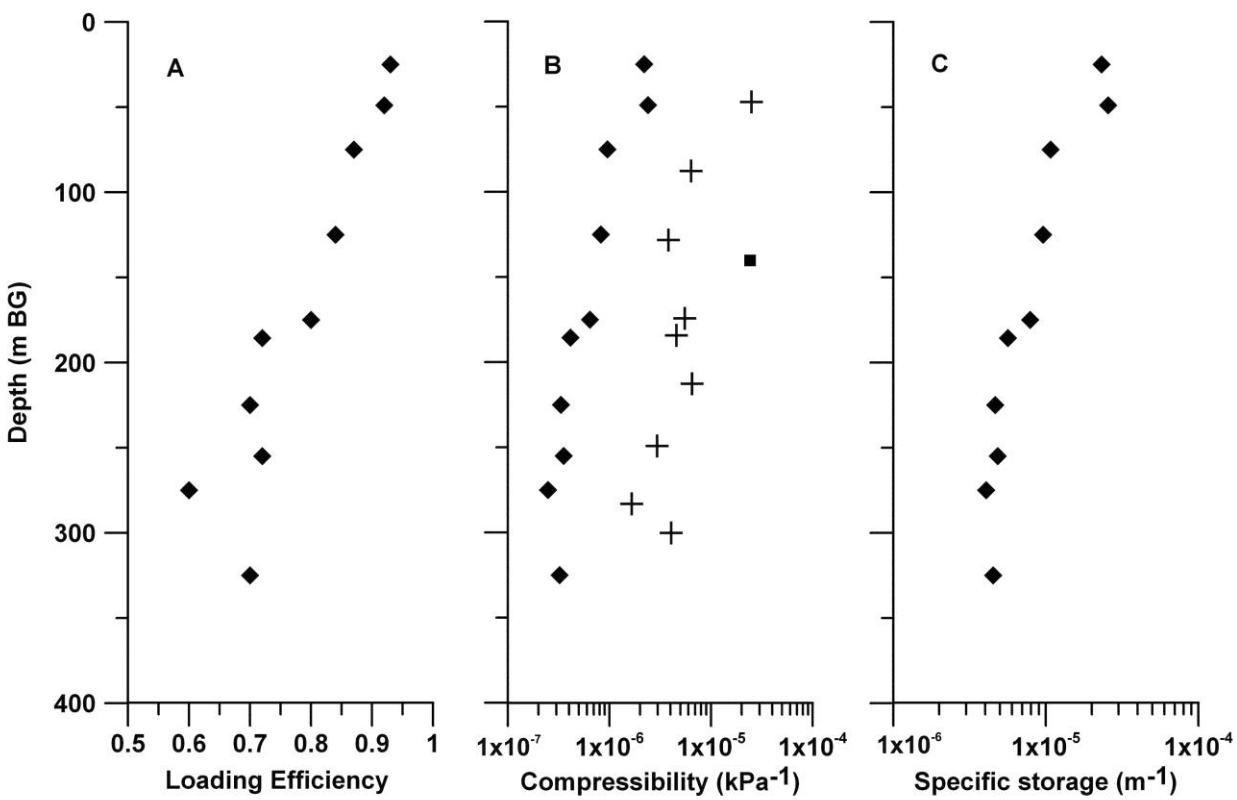

Figure 2. Loading efficiency determined at the depth of each transducer (A) and the resulting depth profiles for in situ α (B) and Ss (C). Laboratory consolidation tests for the shale (+) and the grout (■) are presented in B in relation to the transducer results (♦) (from Smith et al., 2013).

Conclusions

This study demonstrates how using sensitive pressure transducers can be installed in deep boreholes to provide accurate and reliable in situ parameters of aquitards at depth. The pore pressure recorded by the grouted-in transducers provided evidence that barometric pressure fluctuation, earth tides, and moisture loading could be observed from surface to 325m BG. Using the pore pressure responses to known surface pressure changes (barometric pressure), the loading efficiency of the formation was determined and led to the in situ calculation of α and Ss. The laboratory results of α from core samples obtained from the borehole were found to be as much as an order of magnitude greater than our in situ estimates; indicating lab results overestimate the compressibility of the formation. Furthermore, the ability to install multiple pressure transducers in a single borehole can be used to determine in situ parameters at various depths without having to drill multiple boreholes to achieve the same depth profile. Future work could be directed toward using pressure transducers to monitor and track the effects of various mining practices that cause mechanical or pressure changes (ex. fluid or gas injection) in low K geologic formations.

Acknowledgements

Advice provided by Lee Barbour (University of Saskatchewan) and Randy Schmidt (Environment Canada) is greatly appreciated. Funding was provided by NSERC-IRC, Mosaic, PotashCorp and Cenovus.

References

Anochikwa, C. (2010), A coupled stress-flow numerical modelling methodology for identifying pore-pressure changes due to total soil moisture loading, M.S. thesis, Dep. of Geol. and Geophys., Univ. of Saskatchewan, Saskatoon, Saskatchewan, Canada.

Bishop, A. W. (1973), Influence of an undrained change in stress on the pore pressure in porous media of low compressibility. *Geotechnique, 23* (3), 435–442.

Cherry, J. and B. Parker, (2004), *Role of Aquitards in the Protection of Aquifers from Contamination: A "State of the Science" Report.* Denver, Colorado: AWWA Research Foundation.

Grisak, G. E. and J.A. Cherry (1975), Hydrologic characteristics of response of fractured till and clay confining a shallow aquifer. *Can. Geotech J., 12*, 23–43.

Jacob, C. (1940), On the flow of water in an artesian aquifer. *Trans. Am. Geophys.Union, 21*, 574-586.

Keller, C. K., G. van der Kamp, and J. A. Cherry (1986), Fracture permeability and groundwater flow in a clayey till near Saskatoon, Saskatchewan. *Can. Geotech. J., 23*, 229–240.

Keller, C. K., G. van der Kamp, and J. A. Cherry (1989), A multi-scale study of permeability of thick clayey till. *Water Resour. Res., 25* (11), 2299-2317.

Klohn, E. J. (1965), The elastic properties of a dense glacial till deposit. *Can. Geotech. J., 11* (2), 116–128.

Neuman, S. and P. Witherspoon (1972), Field determination of the hydraulic properties of leaky multiple aquifer systems. *Water Resour. Res., 8* (5), 1284–1298.

Radhakrishna, H. S. and T. W. Klym (1974), Geotechnical properties of very dense glacial till. *Can. Geotech. J., 11*, 396–408.

Shaver, R. B. (1997), The determination of glacial till specific storage in North Dakota. *Ground Water, 36* (4), 552–557.

Skempton, A. W. (1954), The pore-pressure coefficients A and B. *Geotechnique, 4*, 146–147.

Smith, L.A., van der Kamp, G., Hendry, M.J. (2013), A new technique for obtaining high resolution pore pressure records in thick claystone aquitards and its use to determine in situ compressibility. Water Resour. Res., 49 (2) 732-743.

Terzaghi, K. (1923), Die Berechnung der Durchlässigkeitsziffer des Tones aus dem Verlauf der hydrodynamischen Spannungserscheinungen. *Sitz. Akad. Wissen. Wien d. matem.-naturw.Kl., part IIa, 132*, pp. 125–138. [English translation by C. R. I. Clayton and H. Müller Seinhagen: A method of calculating the coefficient of permeability of clay from the variation of hydrodynamic stress with time. As cited in Clayton, C. R. I., H. M. Steinhagen, and W. Prowrie (1995), Terzaghi's theory of consolidation, and the discovery of effective stress. Proceedings of the Institution of Civil Engineers. *Geotech. Engin. 113* (4), 191–205.]

Terzaghi, K. and K. O. Frohlich (1936), Theorie der Setzung von Tonshichten: eine einfuhrung in die analytische Tonmechanil, Leipzig, Franz Deuticke. [As cited in Terzaghi, K., R.B. Peck and G. Mesri (1996), Soil mechanics in egineering practice (third edition), John Wiley and Sons, New York. NY, USA.]

Terzaghi, K., R. B. Peck, and G. Mesri (1996), *Soil mechanics in engineering practice* (third ed.). New York, NY, USA: John Wiley and Sons.

van der Kamp, G. (2001), Methods for determining the in situ hydraulic conductivity of shallow aquitards - an overview. *Hydrogeol. J., 9*, 5–16.

van der Kamp, G. and J. E. Gale (1983), Theory of Earth tide and barometric effects in porous formations with compressible grains. *Water Resour. Res., 19* (2), 538–544.

van der Kamp, G. and R. Schmidt (1997), Monitoring of total soil moisture on a scale of hectares using groundwater piezometers. *Geophys. Res. Lett., 24* (6), 719–722.

Wang, H. F. (2000), *Theory of Linear Poroelasticity with Applications to Geomechanics and Hydrogeology*, Princeton University Press, Princeton, NJ.