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Profiling the *in situ* compressibility of cretaceous shale using grouted-in piezometers and laboratory testing

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HIGHLIGHTS

- In situ measurements of m_v were conducted in the Williston Basin shales at two sites.
- Measured m_v profiles at both sites produced similar trends of decreasing m_v with increasing depth.
- Stress behaviour observed in laboratory tests indicate a pattern that can be applied to the in situ profiles.

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ABSTRACT

Grouted-in vibrating wire pressure transducers (VWPs) can be used to measure the *in situ* laterally constrained compressibility (m_v) of deep claystone aquitards through measurement of barometric loading efficiency. Here, we present the results from 27 VWPs installed in overconsolidated argillaceous glacial till and claystone formations in southern Saskatchewan, Canada at two sites over depths ranging from 10–325 m below the ground (m BGS). The measured m_v profiles at both sites produced similar trends of decreasing m_v with depth. The trends in compressibility with depth were compared to the results from laboratory consolidation testing of core samples taken from the same Cretaceous shale profile. An apparent pre-consolidation pressure $\left(\sigma_c'\right)$ compression index (C_c), and the swelling index (C_s) were determined using 1-D consolidation testing. These tests yielded C_c values ranging from 0.12–0.41 ($\bar{x} = 0.27 \pm 0.11$) andC_s from 0.015–0.09 ($\bar{x} = 0.05 \pm 0.03$). The theoretical depth profile for m_v (during unloading) was calculated for a range of compression indices (C_c, C_s) and the *in situ* void ratio (e)estimated from the consolidation testing, the vertical effective stress $\left(\sigma_v'\right)$ calculated based on the effective unit weight of overburden and laboratory determined preconsolidation values $\left(\sigma_c'\right)$. Varying the values of σ_c', C_c, or e in the hypothetical depth profile demonstrated minor influences on these profiles when compared to that of. The resulting theoretical profiles of m_v with depth $\left(\text{or } \sigma_v'\right)$ exhibited a similar pattern to the laboratory and field observations; however, for the laboratory test data to replicate the *in situ* profiles, the laboratory measured values of C_s had to be reduced by an order of magnitude in order to compensate for both the applied strain increment differences, as well as sample destruction during recovery and testing. The good agreement between the theoretical and the *in situ* measured m_v profiles with depth highlight the potential to combine *in situ* measurements of m_v with laboratory consolidation test results to characterize the mechanical properties of deep claystone aquitards.

1. Introduction

Low-permeability ($k \leq 10^{-8}$ ms^{-1}) argillaceous sediments (clay-rich aquitards) are globally widespread, making up two thirds of all sedimentary rocks on Earth. Characterizing the hydrogeologic properties of these aquitards is important to understand the sources and distribution of natural resources in sedimentary basins, which contain the largest repositories for oil and gas in the world, as well as contain extensive evaporite deposits (potash, anhydrite, halite, etc.). These claystone aquitards (commonly referred to as shales) can also act as caprock formations restricting oil or gas migration to surface or into overlying shallow aquifers during unconventional resource extraction processes (e.g., steam-assisted gravity drainage and cyclic steam stimulation). Moreover, the low-k and high sorption capacity of thick basinal aquitards makes them possible host formations for the sequestration of hazardous wastes.[1–3]

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Characterizing the hydraulic and hydro-mechanical properties of these deposits has been difficult due to the slow response times of field-based hydraulic test methods and the difficulty in recovering representative 'undisturbed' samples due to the high degree of state dependence and susceptibility to moisture-induced degradation. In addition, stress changes can cause void ratio variations that can affect both the k and stiffness of the material, as well as generate excess pore water pressures that require time to dissipate before the final strain state of the material is achieved.[4] Even when intact samples are carefully collected, conventional laboratory testing of core samples generally overestimates the one-dimensional (1-D) constrained compressibility (m_v), and underestimates k by orders of magnitude.[5–7] This study provides a better understanding of the stress behaviour of argillaceous aquitards using a new approach to compare the profiles of m_v with depth, using *in situ* methods. The findings are then compared to those obtained from laboratory and theoretical estimates. It is proposed that the use of the *in situ* methods for determining the stiffness of the ground within low permeability formations can effectively eliminate the need for complex sampling and testing methods.

2. Site location

Two sites, located in the Canadian portion of the Williston Basin (WB) were investigated. Site 1 is located on the northeast portion of the WB where the surficial till is thin (<10 m) relative to other regions in the basin (Fig. 1a). Site 2 is located approximately 350 km southwest of Site 1, and closer to the centre of the basin (Fig. 1a). A single borehole was continuously cored at Site 1 in 2009 using water and bentonitic drilling mud to a total depth: 325 m BGS., Another five boreholes were continuously cored at Site 2 from 2012 to 2014 to a total depth: 100–200 m BGS. The five boreholes at Site 2 were within a 180 km^2 area and although the formations were the same, the depth to the till/shale contact varied from 35–75 m BGS. Core samples (measuring 75 mm in diameter, and 150 mm long in length were collected every 10 m from each borehole. Samples were trimmed to remove any drill fluid, sealed in plastic wrap, waxed in the field, and stored in a cooler at an ambient surface temperature of 5–10 °C until they were transported to the University of Saskatchewan where they were stored at room temperature for 30 to 60 days prior to testing. Nested vibrating wire pressure transducers (VWPs) (n = 3–10) were installed in the 5 boreholes at the two sites (Fig. 1b) to measure fluid pressure at each point. The scale of the VWPs ranged from −0.1 to 0.35, 0.7, 1, 2, and 3 MPa (absolute accuracy of ±0.1% full scale (FS) and resolution of ±0.025% FS). Low-pressure transducers were installed near the surface in order to minimize the error of each measurement. At both sites, the transducers were attached to the outside of a steel tremie pipe and lowered into the borehole. A bentonite/cement grout mixture was pumped down the tremie pipe until grout returned to surface, indicating the entire borehole was filled with grout and the transducers were secured in place directly within the grout. The grout used at both sites was a mixture of 4% bentonite–96% cement. It was regularly tested during installation to ensure the specific gravity was approximately 1.7.

The transducers were connected to a datalogger and programmed to record pressure and temperature at 30 min increments following installation. Stabilized hydraulic heads were corrected for barometric pressure following the method described in Ref. 6, in which the loading efficiency (γ) for the formation at the location of each transducer was determined and pore pressure records corrected accordingly to define hydraulic head. *In situ* values of m_v were then calculated for each VWP location throughout Site 1 and Site 2 using[8]:

$$m_v = \frac{\gamma n \beta}{1-\gamma} \tag{1}$$

where n is porosity, and β is the bulk compressibility of water (4.6 × 10^{-7} kPa^{-1}).

Several of the recovered core samples were collected for 1-D consolidation testing (ASTM D2435-04[9]) from the shale formations at Site 1 at depths of 47.4, 87.0, and 128.4 m (Pierre Shale), 174.1, 184.9, 212.0 and 249.0 m (1st Speckled Shale), 283.6 (2nd Speckled Shale) and 292.0 m (Belle Fourche Shale). Each sample was 63.3–63.5 mm in diameter and 12.5 to 13 mm in height. Incremental loading stages (n = 8–10), each lasting 10–12 h, were applied to each specimen (with stresses increasing from approximately 0.06 MPa and up to 58 MPa, which is the limit of the test equipment). The results were corrected for compressibility of the apparatus by loading a steel blank over the loading range. Additional core samples were obtained from the shale at both sites to calculate total porosity (n_T) in accordance with ASTM D4531-86[10] (n = 45 from Site 1; n = 28 from Site 2).

3. Results and discussion

The glacial till at both sites is often referred to as Quaternary drift. The drift is composed of the Sutherland and the Saskatoon Groups, and both groups are composed of overconsolidated silt and clay with various accumulations of coarser and finer fractions. Generally, the two Groups are differentiated based primarily on laboratory testing (e.g. carbonate content, Atterberg limits, apparent preconsolidation pressure) and geophysical signatures (cf. Refs. 11–13). The Pierre Shale at both sites is primarily grey–dark grey, non-calcareous, overconsolidated silt and clay. Shell fragments, fossils, and pyrite mineralization have also been observed at various horizons throughout the formation. Thin layers (<50 mm) of bentonite are also common throughout the Pierre Shale. Both the 1st and 2nd Speckled Shale are calcareous mudstones with abundant coccoliths and coccospheres producing a 'speckled' appearance. There are also minor amounts of bentonite, fossils, and concretions in both formations and are often only distinguished by the high total carbon content and hydrogen indices of the 2nd Speckled Shale. Both the Belle Fourche and Joli Fou Formations are composed of greyish black shale, and are separated by a marker bed at the base of the Belle Fourche known as the 'fish scales zone'. The Mannville Group is generally divided into an upper and lower portion. The upper zone is composed of interbedded marine shale and sandstone and the lower zone is composed of interbedded continental sand and shale.

The total porosity (n_T) values measured from recovered core samples at Sites 1 and 2 are consistent, decreasing slightly with depth (Figs. 2 and 3). The mean ($\bar{x}$) n_T of Site 1 and Site 2 are 0.33 ± 0.04 (n = 45), and 0.33 ± 0.02 (n = 28), respectively. These values are consistent with measured values from the Lower Colorado shales near the Fort ala Corne forest 160 km north of Saskatoon ($\bar{x}$ = 0.33 ± 0.05; Schmeling[14]), while values of 0.31 to 0.34 is reported for the Pierre Shale in South Dakota.[15,16] It is well understood[17] that m_v and k are related to the void ratio (e) at a given stress increment. The n_T values were converted to e and assessed for both Site1 and Site 2. The mean indicial void ratios, e_0 at Site 1 and Site 2 are 0.49 ± 0.1 (n = 45), and 0.49 ± 0.05 (n = 28), respectively (Fig. 3). The unit weight of the shales from both sites is generally consistent and averages of 20.9 ± 1.1 and 20.1 ± 0.32 kN m^{-3} from Site 1 and Site 2, respectively. The liquid limits (LL) determined for the Pierre Shales at both Site 1 and Site 2 are also presented in Fig. 3. While there is some variance between sites, they follow a similar trend with depth, and suggest that the shales at the two sites are similar, though not identical. The LL at Site 1 ranges from 38%–152% ($\bar{x}$ = 80.9 ± 30.7) and the LL at Site 2 ranges from 58%–144% ($\bar{x}$ = 95.6 ± 22.8). The results of a standard two-sample t-test assuming unequal variance, indicates that there is not enough evidence to reject the null hypothesis that the two sample means are the same (p-value = 0.06).

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