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Determination of consolidation behaviour of clay slurries

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ABSTRACT

The main objective of this study was to determine the consolidation behaviour of clay slurries. A fine-grained clay with high consistency limits ($w_L = 180\%$, $w_P = 120\%$) was investigated using conventional oedometer and bench-top centrifuge tests. Results indicated that the slurry had an apparent preconsolidation (due to initial conditions, electrochemical interactions, tortuous drainage, and thixotropic strength) from $e = 5.7$ to $e = 5.5$ followed by virgin compression. Likewise, the low hydraulic conductivity (10^{-10}–10^{-12} m/s) was due to low porosity (small pore throats) and high tortuosity (long flow paths). Unlike consolidation of soils, the c_v and m_v decreased with increasing σ' but increased with increasing e and k. The data from the two tests correlated well in the range of $\sigma' = 10$–65 kPa, $e = 5.5$–3.86, $k = 1.7 \times 10^{-10}$–5×10^{-11} m/s, $F_c = 1$–40 MN. New equations were developed to correlate the consolidation parameters (e, σ', k) with F_c. The deviation of k beyond 40 MN ($e = 4.65$) was due to deviation from the initial straight line portion of the settlement curve in the centrifuge test.

1. Introduction

Several mining operations generate waste tailings that contain variable amounts of clay fraction thereby affecting the consolidation behaviour of such water-rich slurries [1]. The consolidation properties are important for slurry containment facilities and when the slurries are used as backfills [2]. The water release rate and amount is governed by the following factors: (i) self weight due to gravity and applied loading due to upper layer deposition [3–5]; (ii) initial and boundary conditions including the prevalent climate, side and/or bottom drainage and containment geometry [6–8]; (iii) electrochemical interactions between the clay and the pore fluid [9–11]; and (iv) microstructure and thixotropy derived from the above [12–14]. The determination of consolidation properties is based on volume compressibility and hydraulic conductivity relationships obtained from laboratory tests.

Table 1 provides a summary of the various types of consolidation tests used for clay slurries. The first three tests require long time to complete but directly determine the constitutive relationships. In the conventional oedometer test, the hydraulic conductivity measurement can cause consolidation in the low effective stress range if the seepage force is greater than the applied stress. Likewise, the slurry consolidation test uses large samples thereby affecting the spatial variability in material properties. Similarly, the seepage induced test uses a complex equipment setup but is useful in the low effective stress range. Although the continuous loading test and the controlled gradient test require less time, these tests are based on the conventional consolidation theory thereby limiting these tests to small strain applications. Finally, the bench-top centrifuge test generates consolidation data similar to the conventional oedometer test, the seepage induced test, and the continuous loading test [32,33]. There is a need to understand the results of the bench-top centrifuge test (requires the least time) in conjunction with the conventional oedometer test (well established test).

The main objective of this study was to determine the consolidation behaviour of clay slurries using laboratory tests. Initially, the geotechnical index properties were determined for preliminary soil assessment. Next, the conventional oedometer test and the bench-top centrifuge test were conducted. Finally, the test results were compared to convert the former test data to the later test data thereby determining the volume compressibility and hydraulic conductivity relationships.

2. Test methods

The clay was retrieved from a local geological deposit of high plasticity. The samples were collected in situ, secured in sealed plastic bags, and transported to the Geotechnical Testing Laboratory at the University of Regina where these were stored at a temperature of 25 °C. The geotechnical index properties of the active clay were determined according to standard ASTM test

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Table 1
Summary of consolidation tests.

Test type and reference	Test equipment and analysis procedure	Limitations
Conventional oedometer test [15–18]	• D = 60–63 mm, H = 20–25 mm • e–σ': Measured by incremental loading and data analyzed using SSC theory or LSC theory • k: Directly measured using constant/falling head method or indirectly determined using square root of time method	• Long test duration • Direct determination of k may cause consolidation • Scatter in consolidation constants
Slurry consolidation test [9,19–23]	• D = 40–495 mm, H = 150–1800 mm • e–σ': Measured by incremental loading and data analyzed using LSC theory • k: Directly measured or indirectly determined by inversion of LSC theory	• Long test duration if k is directly measured • Spatial variation in material properties in large samples
Seepage induced test [16,19,24,25]	• D = 50–150 mm, H = 20–40 mm • e–σ': Measured by application of hydraulic gradient and data analysis does not require any theory • k: Directly measured using constant head method	• Long test duration • Requires sophisticated instrumentation • Not applicable for high σ' range • e altered due to sample rebound
Continuous loading tests [19,26–29]	• D = 60–254 mm, H = 20–1000 mm • e–σ': Measured by constant rate of stress or strain and data analyzed by inversion of SSC theory or LSC theory with a constant c_v • k: Indirectly determined by inversion of SSC theory or LSC theory	• Compressibility and hydraulic conductivity cannot be validated • Theoretical limitations render it unsuitable for large strains
Controlled gradient test [30,31]	• D = 25 mm, H = 63 mm • e–σ': Measured by controlled gradient by continuously adjusting loading rate and data analyzed by inversion of SSC theory • k: Indirectly determined by inversion of SSC theory	• Loading rate is unknown at the start of the test • Theoretical limitations render it unsuitable for large strains
Bench-top centrifuge test [32–37]	• D = 26–58 mm, H = 20–125 mm • Centrifuge maximum radius: 300–350 mm, rpm: 300–3000 • e–σ': Indirectly determined and data analyzed using scaling laws, LSC models or comparison of results with a different test type • k: Indirectly determined from initial straight line portion of settling curve	• Particle segregation is more likely to occur • No standard procedure to convert centrifuge data to consolidation data

Note: e–σ' – compressibility; e – void ratio; σ' – effective stress; k – hydraulic conductivity; SSC – small strain consolidation; LSC – large strain consolidation; D – diameter; and H – height.

methods as follows: (a) specific gravity (G_s) by the Standard Test Method for Specific Gravity of Soil Solids by Water Pycnometer (ASTM D854(10)); (b) liquid limit (w_l), plastic limit (w_p) and plasticity index (I_p) by the Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils (ASTM D4318(10)); and (c) soil classification by the Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) (ASTM D2487(11)).

Fig. 1 gives the schematic of the conventional oedometer (Model S-450). The test was conducted as per the ASTM Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading (D2435). The clay (up to 20 mm aggregates) was soaked in tap water and was frequently stirred with a steel rod to ensure homogeneous water distribution. The resulting slurry, at a water content ($w = w_l$), was poured in the oedometer ring (63.5 mm diameter and 25.4 mm height). Presaturated porous stones above and below the sample allowed upward drainage, the geotextile precluded porous stone clogging, and the outer casing prevented surface tilting. The loading frame was lowered (touching the steel ball on the loading head to minimize eccentricity) and was fixed in-place using clamps. The combined stress of the loading head, porous stone, geotextile and steel ball measured 1.5 kPa. Subsequent effective stress (σ') increments were pneumatically applied using an air compressor and were maintained through a digitally controlled pressure regulator. A linear vertical displacement transducer (LVDT) was used to record deformations at specified time intervals. A 20 mm water head was maintained on top of the sample to ensure complete saturation throughout the test.

The hydraulic conductivity (k, m/s) after each σ' increment was measured using the falling head method. Upward drainage was allowed (to prevent consolidation) using the hydraulic gradient between a bottom injection tube and the water level in the oedometer ring [38]. The hydraulic gradient was kept less than the critical hydraulic gradient to preclude internal erosion. Several k measurements were made to ensure a reliable value at a given void ratio (e). The test was stopped when two consecutive readings showed no significant change. The k was calculated from knowledge of the internal standpipe area (a, mm^2), sample length (L, mm), sample cross-sectional area (A, mm^2), elapsed time (Δt, s), initial water head (h_1, mm) and final water head (h_2, mm), according to the following version of Darcy's law:

$$k = 0.23\frac{aL}{A\Delta t}\log_{10}\frac{h_1}{h_2} \tag{1}$$

Fig. 2 shows schematic of the bench-top centrifuge test. This setup has been recently used at the University of Regina for oil sand fine tailings [39,40]. The digitally controlled unit (Sorvall Thermo Scientific Biofuge Primo R) comprised of a swinging bucket rotor with four buckets and had a maximum radius of 127.4 mm as shown in elevation (Fig. 2a) and plan view (Fig. 2c). Graduated acrylic tubes (24.2 mm internal diameter and 106 mm height) were filled with the slurry (prepared as before) and placed in ceramic tube-holding adapters in two separate buckets (Fig. 2b). The slurry was filled up to the 40 mm mark which gave a ratio of sample height to centrifuge radius of 1:3, as suggested by McDermott and King [36]. The test was conducted at a constant temperature of 20 °C and an angular velocity of 4000 r/min. The centrifuge was stopped at specified time intervals and the interface height of the sediment was noted (Fig. 2d). The measurements were taken from both tubes and the average value was recorded. Using H_t (mm) for the interface height, H_o (mm) for the initial interface height and e_o for the initial void ratio, the e was calculated using the following equation [33]:

$$e = \left(\frac{H_t}{H_o}\right)(1 + e_o) - 1 \tag{2}$$

Likewise, the centrifugal force, F_c (MN) was computed using the following equation [32]:

$$F_c = mr\omega^2 \tag{3}$$

where m is mass (kg) of the slurry, r is radius (m) that is the centroid of the slurry mass and $w = (rpm/60)2\pi$ is the angular velocity (1/s). The centrifugal force was applied to the specimen in 1 s and