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Consolidation Characteristics of Wastewater Sludge

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Abstract: Capping is a cost-effective remediation method for soft contaminated sludge. The Madison Metropolitan Sewerage District evaluated different remediation alternatives to treat its polychlorinated biphenyl (PCB) contaminated sludge and the U.S. EPA agreed to permit capping as the method of remediation. Design of the cap required knowledge of the consolidation behavior of the sludge. In order to analyze this behavior, a series of consolidation tests was performed. The laboratory testing program included three large-scale consolidation tests and four conventional oedometer tests. Consolidation settlement of the sludge was observed in two field test cells capped with a wood chip/soil mixture which was reinforced with a woven geotextile. Instrumentation of the test cells included settlement plates, surface survey markers, and piezometers at different depths in the sludge. Laboratory and field observations were compared with results from conventional consolidation theory and a nonlinear finite-strain (large strain) numerical model (CS2). Conventional theory exhibited some limitations in analyzing the results and underpredicted the time for completion of consolidation. However, the large strain model more accurately predicted the behavior observed in both the laboratory and the field.

Keywords: sludge, consolidation, hydraulic conductivity, compressibility, large strain, capping, covers.

Introduction

Construction of an engineered cover or capping system is an efficient and economical component of many in situ containment strategies for contaminated sludges and other high water content waste materials. Considerable evidence has been provided in recent studies (Grefe 1989, Zeman 1994) that containment of soft sediments and papermill sludges by capping, including subaqueous capping, may provide a cost-effective solution.

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The Madison Metropolitan Sewerage District (MMSD) generates sludge as part of its water treatment process. This sludge has been disposed in lagoons and subsequently retrieved as fertilizer for application on farmlands. Some of the sludge contained polychlorinated biphenyls (PCBs) at concentrations above the allowable limit (50 mg/kg) and was banned from land application. The main objective of capping was to isolate the sludge and support the growth of a vegetative cover, thus minimizing exposure to potential ecological receptors. The U.S. EPA has approved this concept of capping as the method of remediation for the lagoons.

A cap constructed over a high water content sludge is subject to considerable settlement that needs to be assessed at the design stage. This paper presents the settlement behavior of MMSD wastewater sludge. Small and large-scale laboratory consolidation tests were conducted and field observations were made for two test cells capped with a wood chip/soil mixture. Field and laboratory results were evaluated using two consolidation models, conventional (infinitesimal strain) theory and nonlinear finite strain (large strain) theory.

Experimental Work

Sludge Characteristics

Sludge samples were obtained from a test cell in Lagoon #2A of the MMSD Nine Springs Wastewater Treatment Plant in Madison, Wisconsin USA. The samples had an average water content of 305%, corresponding to a solids content (weight of solids as percentage of total weight) of 25%. The sludge did not exhibit plasticity. The solid phase of the sludge contained 22-30% fines (<0.075 mm) as determined by wash sieving. The sludge had a mean specific gravity of 1.85 and an organic content of 25%.

Laboratory Consolidation Tests

Large-scale consolidation tests were performed using a slurry consolidometer similar to that described by Sheeran and Krizek (1971) (Figure 1). Small-scale oedometer tests (ASTM D2435) were also performed on four specimens trimmed from a consolidated block generated at the end of one large-scale consolidation test. Preliminary test results indicated that gas generated in the sludge impedes the consolidation process (Aydilek 1996). The effect was not noticeable in the oedometer tests due to the small specimen size. However, this effect was evident from the initial settlement readings of the slurry consolidometer tests. In order to eliminate this problem, a backpressure of 345 kPa was applied to the sludge specimens during testing. Before placement of the sludge in the slurry consolidometers, a woven slit-film polypropylene geotextile (mass per unit area = 203 g/m^2) was placed over the bottom porous stone to prevent clogging with fine particles. This also facilitated the separation of the consolidated block from the lower stone after testing. The same geotextile was also placed on top of the sludge prior to testing.

Three large-scale consolidation tests were performed. The first two were conducted using a single small vertical stress increment (9.65 kPa) which was comparable to the vertical stress expected in the field due to the cap. In these tests, the load was maintained constant on the specimen after the end of consolidation to observe secondary compression. Consolidation was considered to be complete when excess pore pressure at the base of a specimen decreased below the measurement limit (1 kPa). The third test was initiated at a higher vertical stress (15.2 kPa) and continued incrementally to a final stress of 123 kPa with a load-increment-ratio (LIR) of one. Each loading stage was terminated at the end of consolidation, also determined by pore pressure measurements at the base of the specimen. Settlement was measured using a long-stroke dial gage and a potentiometer because of the large deformations. In general, both devices gave comparable results. After each load increment, a hydraulic conductivity test was performed with flow moving from top to bottom of the sludge specimen. Outflow was collected at the base of the specimen (see Figure 1). The hydraulic gradient was smaller than 3 in each test to minimize seepage-induced consolidation. The main objective of the large-scale testing was to determine the large strains caused by small stress increments.

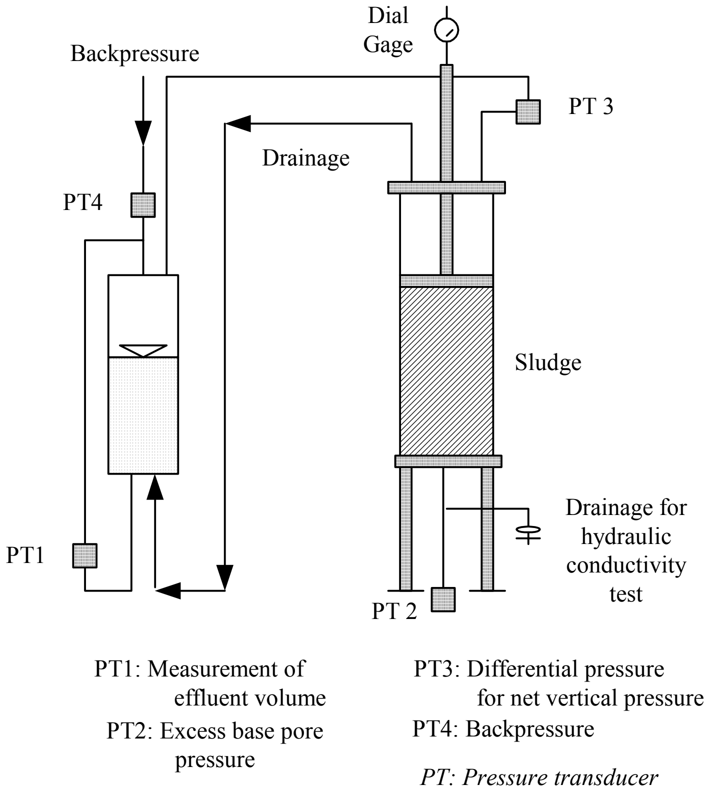

Figure 1- *Large-scale consolidation test*

Sludge specimens for the small-scale oedometer tests were obtained from the consolidated block of a single-increment large-scale consolidation test (Large-scale test 1). They were loaded incrementally to a maximum consolidation stress of 50 kPa in the oedometer cell using a load increment duration (LID) of 24 hours and a LIR of one. Backpressure was not applied to the specimens and no hydraulic conductivity tests were conducted between load increments. Drainage was provided at the top of the specimens and base pore pressures were monitored with a pressure transducer. Table 1 provides a summary of the laboratory consolidation test program.

Table 1 – *Summary of laboratory testing program.*

Test No.*	Initial water content, w_o (%)	Initial void ratio, e_o	Vertical effective stress, σ' (kPa)	Final void ratio, e_f	Final strain (%)
S1	306	5.66	6.25, 12.5, 25, 50	3.98	4.3, 8.4, 15, 25
S2	284	5.25	6.25, 12.5, 25, 50	3.30	7, 12.8, 21, 31
S3	256	4.74	6.25, 12.5, 25, 50	3.14	4, 8.8, 16.8, 28
S4	230	4.26	6.25, 12.5, 25, 50	2.72	5.5, 12, 19.4, 29
L1	367	6.77	9.65	4.97	24
L2	302	5.57	9.65	4.39	18
L3	389	7.18	15.2, 30.4, 60.8, 123	4.14	19.7, 26.4, 30.8, 37

*S = small-scale consolidation (oedometer) test, L= Large-scale consolidation test

Results of Laboratory Tests

Large-Scale Consolidation Tests

Vertical strains for the first stress increment of the large-scale tests were much larger than those observed in the small-scale tests (Table 1) because of higher initial water contents. Test L1 continued for 100 days under constant vertical stress to observe the secondary compression behavior (Figure 2). It is interesting to note that a tertiary compression behavior, as reported for peats and dredgings (Edil and Dhowian 1979, Krizek and Salem 1974) was also observed for the MMSD wastewater sludge. The

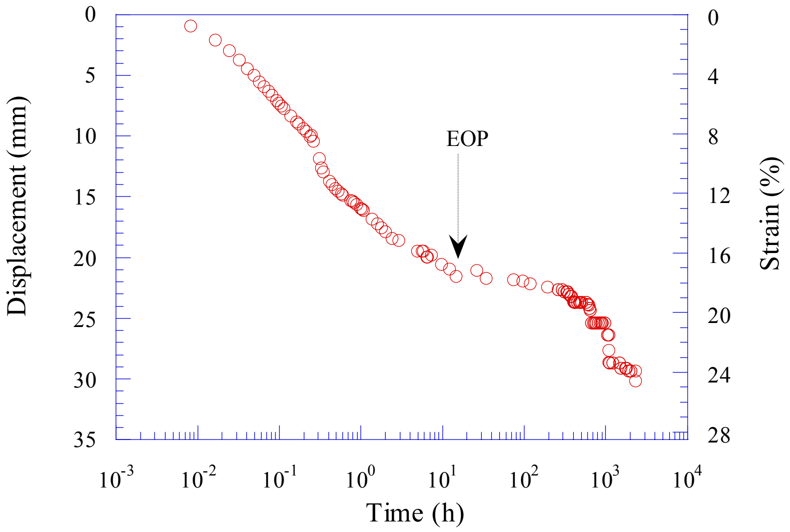

Figure 2 – *Displacement versus time for large-scale test 1*

coefficient of secondary compression (C_α) observed after the end of primary consolidation (EOP), but prior to tertiary, was 0.062. The sharp increase of C_α observed after 500 hours may be due to decomposition of organic matter in the sludge (Fox et al. 1999).

Plots of void ratio versus stress for the large-scale consolidation tests did not show a consistent relationship due to the different initial void ratio (e_o) for each test. Figure 3a shows a plot of void ratio change (Δe) from the initial value versus stress. The measurements obtained in field tests are also shown for comparison. The decrease in Δe with increasing stress is given by the following approximation:

$$\Delta e = 1.402\log(\sigma') - 0.058 \qquad (1)$$

where σ' is vertical effective stress (kPa).

The coefficient of compressibility ($a_v = -de/d\sigma'$) is plotted versus σ' in Figure 3(b). Except for the first stress increment in the large-scale test, a_v values are quite comparable between the small and large-scale tests.

Values of hydraulic conductivity from the laboratory consolidation tests are shown versus void ratio in Figure 3c. This figure also includes another relationship based on data obtained from field tests and laboratory gradient ratio tests (ASTM D5101) performed in connection with a separate investigation of the filtration properties of geotextiles. The logarithm of k decreases linearly with decreasing e; however, the slope of the relationship is not one-half of the initial void ratio as has been reported for many clays (Mesri et al. 1994). Laboratory hydraulic conductivity values decrease from 7.8 x 10^{-6} m/s to 1.2 x 10^{-9} m/s as the void ratio decreases from 7.20 to 4.14. The following function was fitted to the hydraulic conductivity data:

$$\log k = 1.245e-14.07 \qquad (2)$$

where k is vertical hydraulic conductivity (m/s). Equation 2 is similar in form to corresponding relationships observed for other high water content geomaterials; however, the magnitude of hydraulic conductivity and void ratio vary with material and composition (Wang and Tseng 1993). The slope of the linear relationship appears to be higher than that typically observed for clays.

Small-Scale Consolidation Tests

Results of the conventional (small-scale) consolidation tests are summarized in Figure 4. The slope of e-logσ' curve, i.e., compression index, C_c, progressively increases with increasing stress (Figure 4a). Values of C_c for most natural clays are less than 1, and typically less than 0.5. The data in Figure 4 indicate that the MMSD sludge samples have C_c = 1 to 2 and classify as highly compressible having $C_c/(1+e_o)$ greater than 0.2. The relationship between a_v and σ' is shown in Figure 3b.

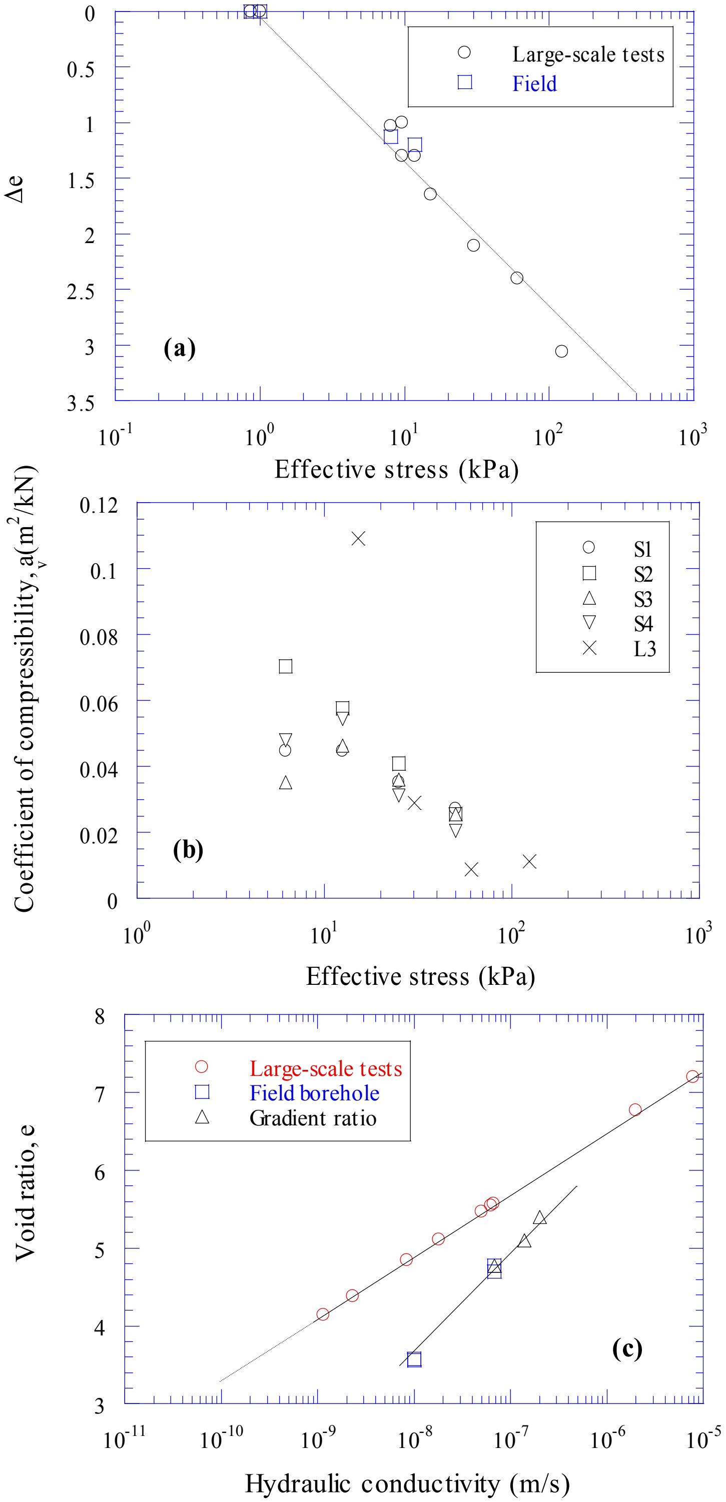

Figure 3 - *Results of large-scale consolidation tests*

Rate of compression was observed to decrease with time under any given load; however, the void ratio versus log-time relationship did not exhibit the classic "S" curve as observed for clays. Nevertheless, coefficient of consolidation (c_v) values were calculated in accordance with the Taylor method and are given in Figure 4b. Due to the shape of the displacement versus time curves, the Casagrande method was not applicable. c_v varies from 5.1 x 10^{-8} to 1.7 x 10^{-6} m^2/s for the sludge and, in general, decreases with increasing effective stress. The coefficient of consolidation typically varies from 3 x 10^{-9} to 1 x 10^{-7} m^2/s for most clays (Duncan 1993). The c_v values obtained for MMSD sludge specimens are generally higher than those reported for clays, which indicates a higher rate of consolidation for this material.

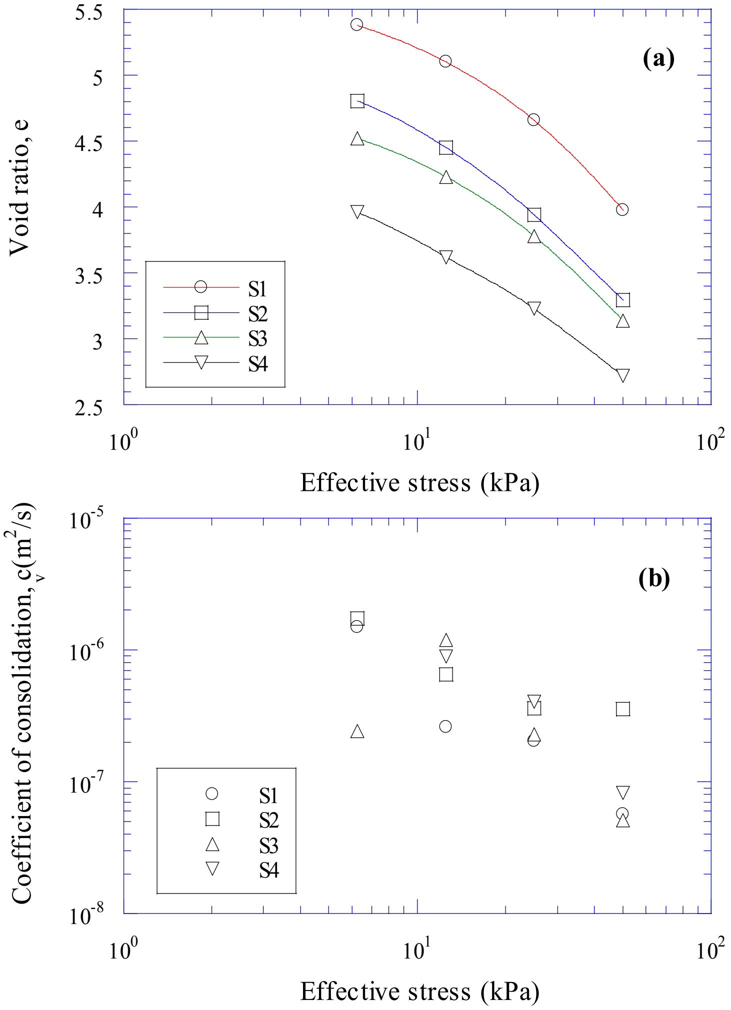

Figure 4 - *Results of small-scale (conventional) consolidation tests*

Field Studies

To investigate the consolidation of MMSD sludge in the field, two test cells were capped using a light-weight fill (i.e., a wood chip/soil mixture). The cells were constructed in two different seasons, summer and winter, to observe seasonal effects on constructability. Total and differential settlement of the cap due to consolidation of the underlying sludge is an important design issue. Geosynthetic reinforcement (woven geotextile) was installed below the lightweight fill to provide stability, but did not significantly affect the total settlement of the cap. However, the presence of a strong geotextile with good filtration characteristics helps to reduce differential settlement and retain sludge solids.

Test Cell 1 was constructed on a 24 m long by 19 m wide section of Lagoon 2A, on August 2, 1996 (Edil and Aydilek 1996). The test cell was confined on three sides with dikes and open on the fourth side. Before construction, the sludge had an average solids content of 25%, corresponding to a water content of 300%, and an average depth of 1.2 m. The sludge was stored in the lagoon for more than 10 years; therefore, sedimentation and self-weight consolidation were assumed to be complete. First, a woven slit-film polypropylene geotextile (mass per unit area = 203 g/m^2) was placed on the in-place sludge to facilitate placement of the cap. The cap was composed of a wood chip/soil mixture with a wet unit weight ranging from 7.5 kN/m^3 to 10.4 kN/m^3 as determined from sand cone tests. The west section of the cap was generally compacted more than the east section (Figure 5) due to a higher number of equipment passes during construction. As a result, cap thickness and the applied stress was not uniform over the sludge. The applied stress was approximately 11 kPa on the west section and 7.6 kPa on the east section (there are local areas where the applied stress was as low as 5.5 kPa) based on cap thickness and density measurements.

Settlement of the sludge was monitored using two settlement plates, one on the west side and the other on the east side, set on the geotextile (Figure 5). Ten open tube piezometers placed at different locations and depths were used to observe groundwater

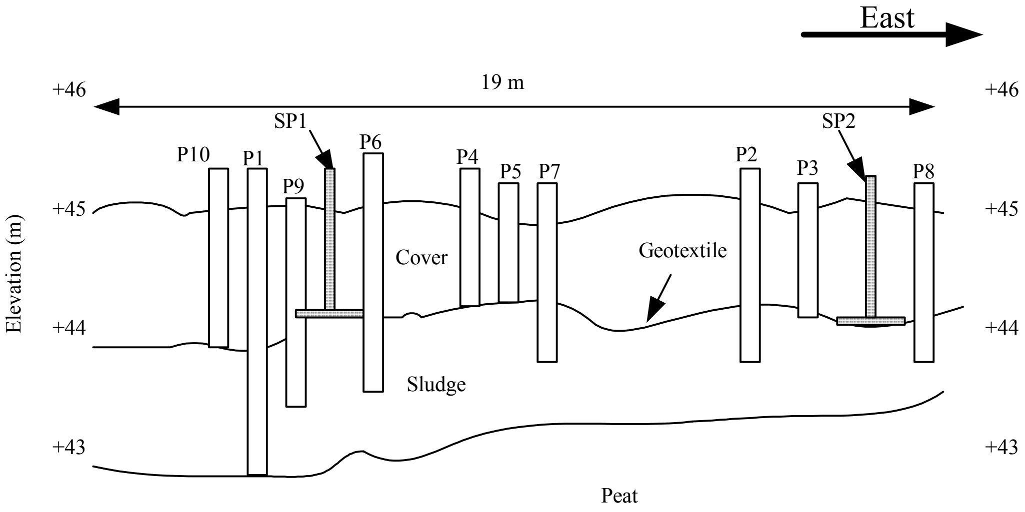

Figure 5 - *Instrumentation of field Test Cell 1*

levels and excess pore pressures during consolidation. Instrumentation of the cell also included nine surface survey blocks to monitor settlement of the cap.

The settlement plates indicated that a settlement of 0.16 m occurred on the west side of the cell (initial thickness, $H_o = 1.33$ m) during construction and another 0.28 m of settlement was observed in the following 2 years; this corresponds to a total strain of 33%. Corresponding values for the east side ($H_o = 1.14$ m) were 0.15 m, 0.21 m, and 31%, respectively. Post-construction surface movements, as indicated by the survey blocks, ranged from 0.05 to 0.14 m.

Excess pore pressures were computed from the difference in water levels for piezometers inserted in the sludge relative to those with their tips at the bottom of the cap. Figure 6 shows that excess pore pressures were close to zero on October 1, 1998 (nearly 800 days after construction) and consolidation was essentially complete. The maximum excess pore pressure was registered in piezometer P1 with its tip at the bottom of the sludge. This suggests that drainage into the peat at the bottom was limited.

To obtain the change in hydraulic conductivity due to settlement of the sludge, cased borehole slug tests were conducted before and after cap construction. A measured amount of water was added into the piezometers and the change in water level was determined over time. As this test is similar to the first stage of Boutwell borehole tests (Daniel 1989), the following equation was used to calculate the hydraulic conductivity:

$$k = \frac{D}{(t_2 - t_1)} \ln\left(\frac{H_1}{H_2}\right) \tag{3}$$

where D is the inner diameter of the piezometer tube, and H_1 and H_2 are the initial and final heights of water in the piezometer, respectively, at times t_1 and t_2. Values of hydraulic conductivity measured by this method reflect mostly the effect of vertical flow; however, the effect of horizontal flow is also included to a certain extent.

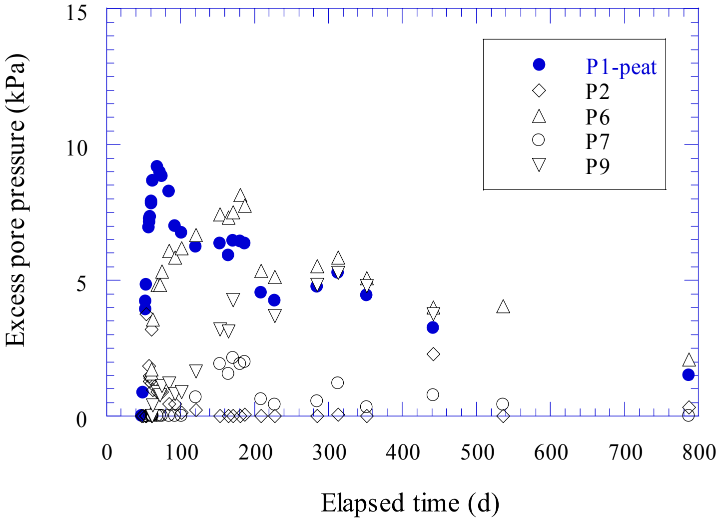

Figure 6 - *Excess pore pressures measured for Test Cell 1*

Figure 3c shows that field hydraulic conductivity values were higher than corresponding values obtained from the large-scale consolidation tests. This is most probably due to the heterogeneous structure of the sludge in the field and possible anisotropic effects. The decrease in field hydraulic conductivity with decreasing void ratio can be characterized by,

$$\log k = 0.78e - 10.86 \qquad (4)$$

where k is in m/s.

The construction of Test Cell 2 was performed during the winter (February 12, 1997) and was facilitated by a 60 mm thick layer of ice over a 0.3 m thick layer of frozen sludge. The frozen sludge was underlain by a 1 m thick layer of soft sludge. Test Cell 2 was constructed using the same reinforcement geotextile and wood/chip soil mixture. The wet unit weight of the cap material was 6.3 kN/m^3 on the northwest side and 10.5 kN/m^3 on the east side. The vertical stresses ranged from about 3 kPa to 9 kPa. These values were lower than those for Test Cell 1.

Before construction, the sludge had an average solids content of 18%, corresponding to a water content of 470%. To evaluate settlement behavior of the sludge, four settlement plates were placed on the sludge surface. The measurements indicated a settlement of 0.21 m at the east side of the cell through the spring thaw (2.5 months) and another 0.30 m of settlement in the following 17 months, giving a total strain of 36%. Values for the northwest side (where the applied stress was lower) were 0.075 m, 0.26 m, and 30%, respectively. Cap surface settlements determined from the survey blocks were comparable to those for the settlement plates, indicating that the post-construction cap compression was insignificant (Edil and Aydilek 1997). Because of thaw compression, consolidation of the sludge layer due to the cap load was not accurately known; therefore, the settlements of Test Cell 2 were not analyzed.

Modeling of Consolidation

Conventional consolidation (Terzaghi) theory is an infinitesimal strain formulation. Specifically, the theory assumes that the hydraulic conductivity, compressibility, and thickness of the compressible layer remain constant during the consolidation process. However, high water content materials, such as the MMSD sludge, experience large strains during consolidation, thus invalidating these assumptions. To investigate these effects, settlement estimates obtained from conventional theory and a numerical finite strain model (CS2) were compared with measured values from the large-scale laboratory tests. CS2 estimates were also compared with measured field settlements for the two settlement plates of Test Cell 1.

CS2 is a piecewise-linear model for one-dimensional consolidation which accounts for vertical strain of the compressible layer (Fox and Berles 1997). The required input parameters for the program are the initial thickness of the soil layer, initial and final overburden effective stress conditions, initial void ratio at the top of the layer, specific gravity of solids, and void ratio-effective stress (e-σ') and void ratio-hydraulic conductivity (e-k) relationships. The output file gives the settlement and excess pore pressure profile for specific values of time. The model vertically divides the strata into R_j elements. An R_j value between 50 and 100 usually gives satisfactory results (Fox and Berles 1997). Initial trials with different R_j values verified these findings; therefore, R_j = 50 was chosen for the simulations. A G_s value of 1.0 was specified to disable the effect of self-weight consolidation in the model. Since the sludge had been stored in the lagoons for more than 10 years, self-weight consolidation was most likely completed. Therefore, CS2 was used to determine the consolidation due only to the applied surface load from the cap.

Figure 7 provides a comparison of estimates obtained from conventional theory and CS2 with the measurements for the incremental large-scale consolidation test (L3). The Δe values given by Equation (1) were subtracted from the initial void ratio (e_o) for each increment in order to obtain the necessary e-σ' relationship for CS2. The e-k relationship was given by Equation (2) based on the laboratory tests. Estimates of average degree of consolidation, $U_{average}$, (i.e., settlement/initial height) versus time, as given by CS2, were generally in a good agreement with measured values from the laboratory test. Estimates obtained using conventional theory based on initial values of c_v underestimated the time for any given average degree of consolidation. This is due to the limiting assumptions of conventional theory, especially the assumption of constant k.

Settlement estimates from CS2 were compared with measured values from Settlement Plates 1 (SP1) and 2 (SP2) in Test Cell 1 (Figure 8). Equations (1) and (4) were used for the input values of e versus σ' and e versus k. CS2 estimates were in good agreement with observed values in terms of both magnitude and rate of settlement. The use of Equation 2 based on laboratory hydraulic conductivity tests resulted in much slower rates of settlement than those observed in the field.

Conclusions

The consolidation characteristics of a wastewater treatment sludge were investigated using laboratory and field tests. The results were compared with estimates given by infinitesimal strain and large strain consolidation models. The following conclusions are reached as a result of this study:

1) The consolidation characteristics of the sludge were different than those of natural clays. Relative to most clays, the sludge exhibited higher compressibility, higher hydraulic conductivity, and a higher rate of consolidation due to high water content and the presence of organic matter.
2) Large-scale consolidation tests were more effective for the measurement of large compression of the sludge during the first load increment. Both the void ratio and hydraulic conductivity varied with applied consolidation stress in a manner comparable to the behavior generally observed for high water content materials.
3) Field test cells indicated approximately 33% compression over a 2 year period of for sludge with an initial thickness of 1.5 m and an initial water content of 300% under an applied stress of 8 to 11 kPa. Winter frost in the sludge and formation of an ice layer over the sludge facilitates cap construction; however, significant compression occurs

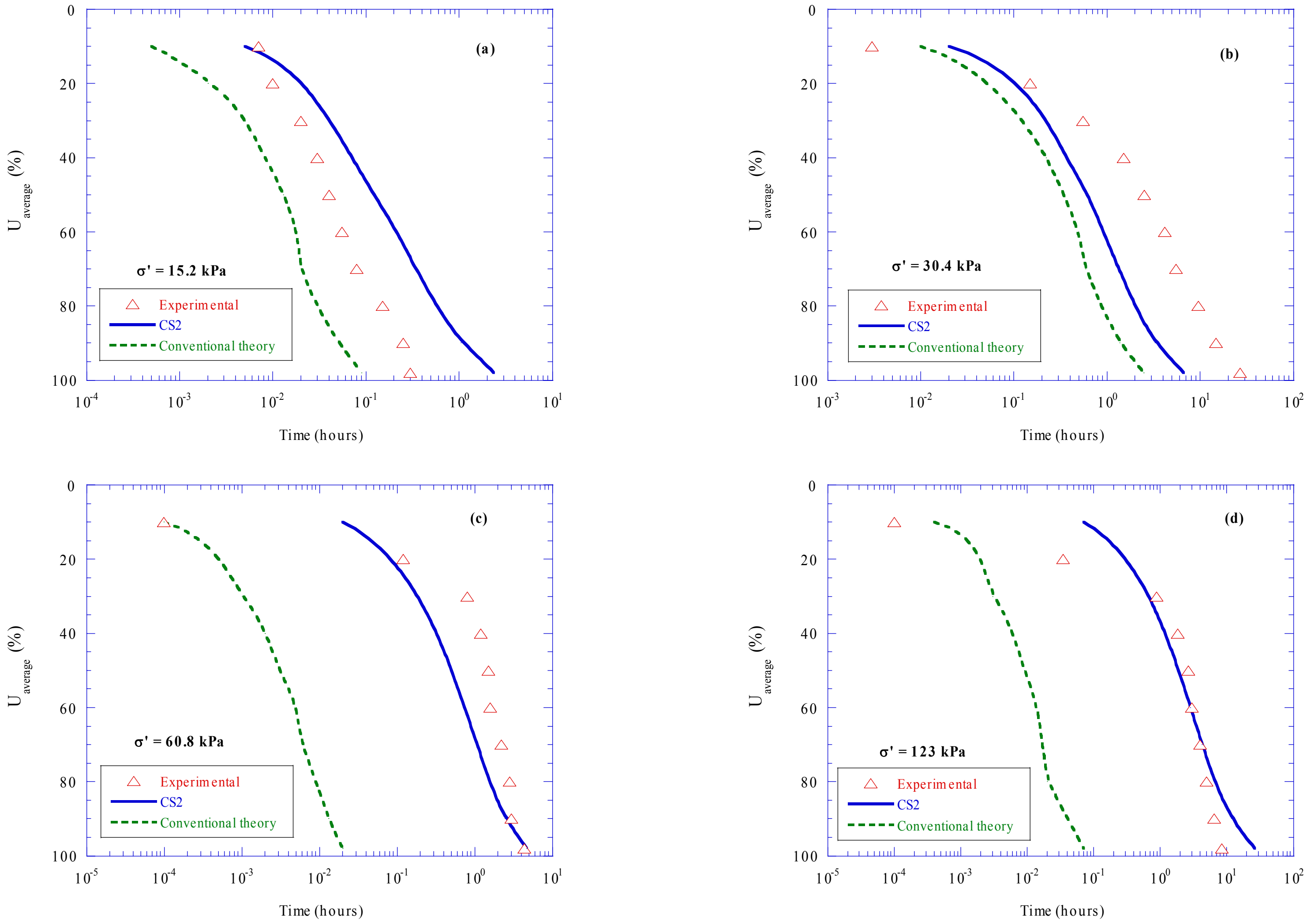

Figure 7. Comparisons of measured and estimated settlements for large-scale laboratory test 3 (L3).

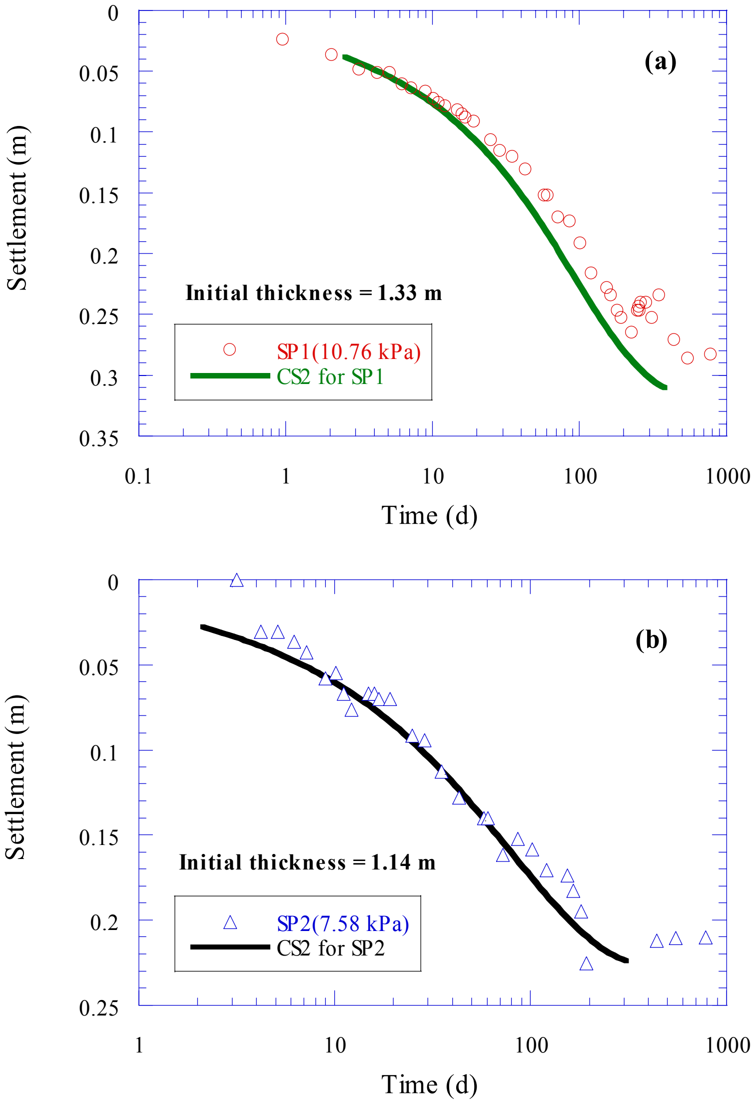

Figure 8 – *Observed and estimated settlements for Test Cell 1: (a) SP1 location and (b) SP2 location*

during the subsequent spring thaw. Large-scale laboratory consolidation tests provided a satisfactory estimate of the magnitude of total settlement in the field.

4) CS2, a numerical code for large strain consolidation, successfully estimated the time required for a given settlement in the field. It also provided a reasonable representation of the large-scale laboratory consolidation tests. Conventional infinitesimal-strain (Terzaghi) theory underestimated the elapsed time for a given average degree of consolidation.
5) The time rate of consolidation is sensitive to the hydraulic conductivity-void ratio relationship. Use of the laboratory hydraulic conductivity-void ratio relationship resulted in an underestimate of the field rate of consolidation whereas the relationship

based on field hydraulic conductivity measurements resulted in good estimate of the field rate of consolidation.

Acknowledgements

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