SETTLING AND CONSOLIDATION BEHAVIOUR OF DREDGED COHESIVE ESTUARINE SOIL USING COLUMN TESTING APPARATUS

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ABSTRACT

Consolidation testing on *in situ* normally or over consolidated cohesive soils is commonly used to assess engineering parameters such as C_v, C_c and C_α. However, the application of conventional consolidation tests to reconstituted soil slurries is often unachievable. A column testing method for assessing the settling and consolidation behaviour of dredged soils was devised and applied to five samples of estuarine soil in a brackish (somewhat salty) water environment sourced from the South Coast of N.S.W, Australia. Test results show that void ratio and bulk density values after the settling phase of the test were comparable with results of *in situ* soil at the initial stage of standard laboratory oedometer testing. Calculation of compressibility coefficients C_c and C_α after the loading stage of the test revealed similar results to oedometer testing on the soils in the *in situ* state. The testing method was assessed to provide results within a more reasonable timeframe with sample thicknesses of approximately 100 mm. It was assessed that soil thicknesses greater than 100 mm in the columns were influenced by simultaneous primary and creep settlement and that an unreasonable test duration would be required to achieve meaningful results in an economic timeframe.

1 INTRODUCTION

Consolidation parameters such as C_v, C_c and C_α are commonly derived from laboratory oedometer tests such as AS1289 6.6.1 (1998) on 'undisturbed', 50 mm or 63 mm diameter soil samples retrieved from site investigation techniques. Frequently these samples show some degree of over–consolidation, enabling the test to be carried out in small diameter ring apparatus without compromising consolidation data. However, consolidation testing of soils that have been reconstituted to a suspension and subsequently settled often cannot be successfully tested using conventional testing methods (Krizek, 2004; Sridharan and Prakash, 1999).

Accessible land with favourable geotechnical properties is becoming limited in society and increasingly areas of reclaimed and contaminated land are being used for infrastructure purposes. Also the offshore disposal of dredged soil is less widely accepted by the community as an acceptable use of dredged soil. The viability of reuse of dredged cohesive soils onland is increasing where previously the cost of reuse of this type of material was considered prohibitive.

In many cases, developing reclaimed or contaminated land often requires the dredging of soils from marine, alluvial and estuarine environments or dredging from mining tailings or contaminated land. In most cases this dredged material is deposited in a holding area (i.e. tailings dam) to be subsequently used as reclaimed land. The nature of the soil as it settles from suspension and various properties such as the rate and magnitude of consolidation settlement must be assessed for decisions to be made as to whether the dredged soil can be reused as reclaimed land.

This paper presents the results of testing performed on cohesive soils sourced from an estuarine environment located on the South Coast of N.S.W, Australia. Significant research has previously been carried out on testing of dredged soil materials in freshwater environments (Krizek, 2004; Sheeran and Krizek, 1971). This paper discusses the settling behaviour of the dredged slurry suspension in brackish water for different soil to water ratios. It also provides assessment of ρ_d and e_o during the settling phase, assessment of consolidation parameters C_v, C_c and C_α. A comparison is also made between the results of the column testing for 'dredged' soil and conventional oedometer testing values from three samples of 'undisturbed' soil.

2 METHODOLOGY

The assessment of settling and consolidation behaviour of the soils was conducted using testing apparatus constructed exclusively for the test. The testing consisted of two phases, named Phase 1 and Phase 2. Phase 1 involved observation of the settling of the slurry suspension, and Phase 2 involved observation of the rate of consolidation over time with the addition of different surcharge weights. Australian Standard AS 1289 6.6.1 (1998) was used as a general reference for testing the procedure; however several modifications were made due to the unique nature of the testing.

2.1 APPARATUS

Fifteen clear Perspex columns with an inner diameter of 94 mm were used and each column had a Perspex base fixed with 'Acrifix' Adhesive and a reinforced collar to maintain a water tight seal and integrity of the joint under additional pressure. A plastic tube was drilled into the side of the column 10 mm from the base, with an outlet fixed to the top of the column.

The columns were firmly fixed to a wall using a metal collar placed near the top of the column to prevent movement (accidental or intentional) during the course of testing.

Prior to the settling phase of the testing, a 20 mm layer of sand was placed at the base of each Perspex column and filter paper was placed over the sand. This provided "two-way drainage" to facilitate consolidation in the laboratory condition. This was carried out in an attempt to quicken the rate of settlement with the knowledge that a theoretical correction can be applied to settlement estimates if only "one-way" drainage exists in the field.

After the settling phase of the testing was completed, an additional filter layer was constructed on the top of the settled soil surface. This included placing a layer of filter paper over the soil surface and a 20 mm thick layer of sand over the paper to facilitate drainage. An additional layer of filter paper was placed on top of the sand drainage layer prior to surcharge load being added.

Surcharge loads were constructed from concrete, pre-cast into PVC pipe with an external diameter of 90 mm. The weights were cured for seven days then weighed and measured to calculate load. The surcharge loads were cut to size to meet target preload pressures that were nominated for the testing procedure. The difference in annulus between the column diameter and the surcharge weight provided a drainage path for pore water to pass out of the consolidating soil, into the upper filtration layer and subsequently add to the column of 'free water' that existed above the consolidating soil.

A schematic diagram of the column testing apparatus is presented in Figure 1 and Figure 2.

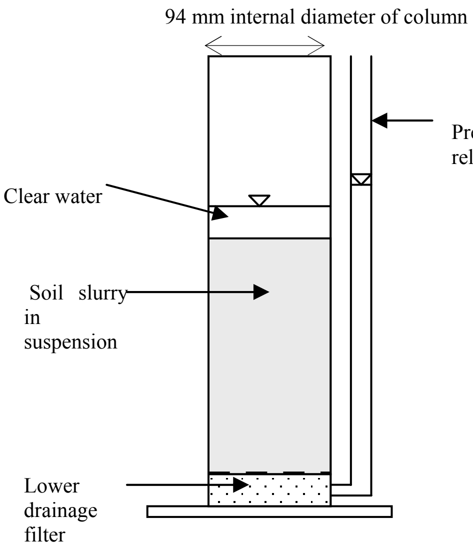

Figure 1: Phase 1.Settling of slurry suspension.

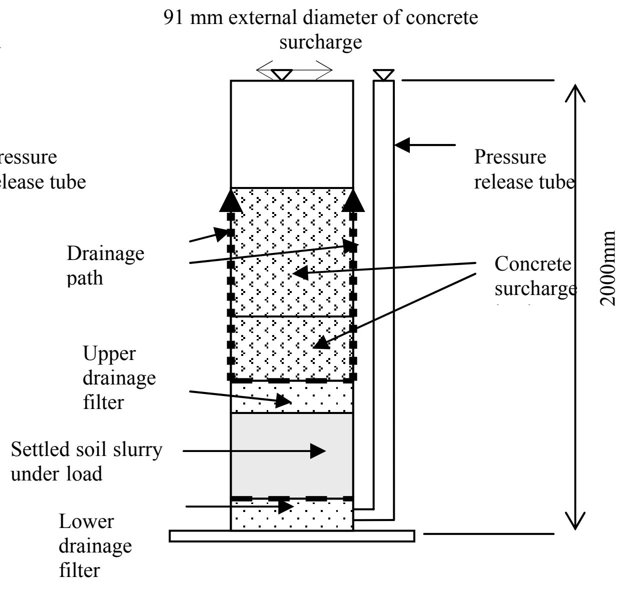

Figure 2: Phase 2 Settled soil under load.

2.2 MATERIALS

The soils used for this testing program were sourced from an estuarine environment located on the south coast of New South Wales. The soils were generally described as sandy clayey silts or silty clays and are typical of Holocene aged estuarine soils found in the region. The natural (initial) moisture content of the five samples of estuarine soils used for this column test ranged between 48% and 133%. No Atterberg Limit testing was carried out on the five estuarine soil samples prior to column testing, however twelve Atterberg Limit tests had been previously carried out on the clayey or silty estuarine soils at the site. Results from these twelve nearby tests are considered to be generally representative of the estuarine soil properties at the site. The Plastic Limit of the twelve nearby soil samples ranged between 15% and 39%, and the Liquid Limit of the twelve samples ranged from 39% to 78%.

To source material for the column test trial, six test pits (designated CGTP21 to CGTP26) were excavated on the 20 January 2004 and six samples were collected that generally represented a variety of estuarine soils at the site. The particle size distributions of the tested samples are presented below in Figure 3. Standard Particle Size Distribution testing including hydrometer analysis according to AS 1289.3.6.2 (2000) was used to assess the silt and clay fractions below 75μm.

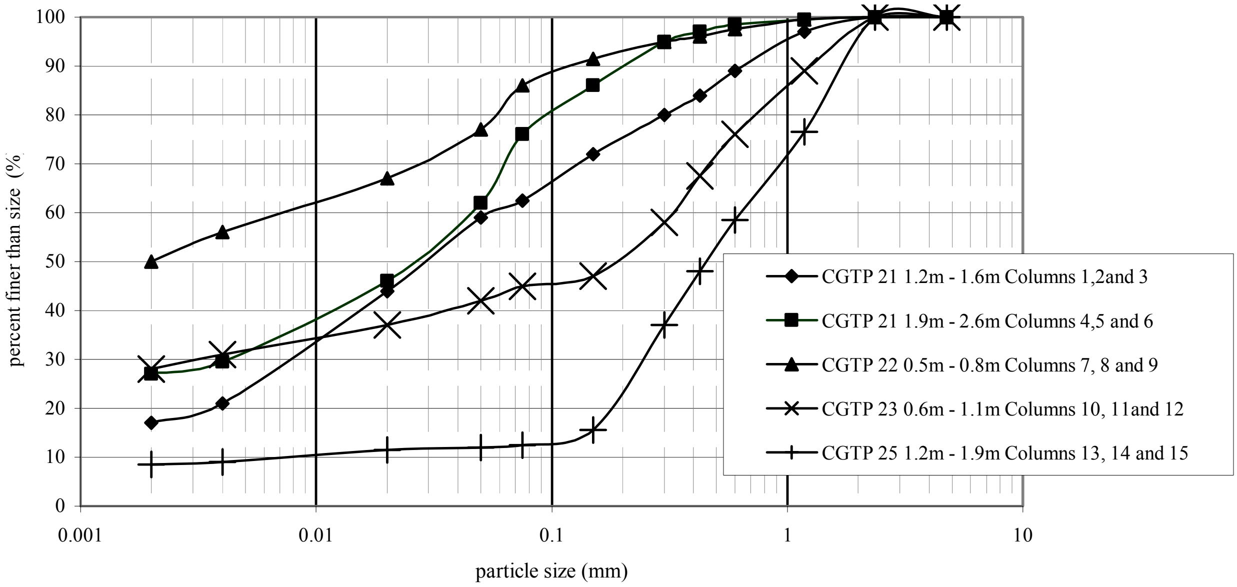

Figure 3: Particle size distributions of tested samples.

Water from the existing swamp on the site was collected for use in the testing procedure. The water was collected approximately 500 m inland and was generally brackish (somewhat salty) with a pH of 6.32. Following collection, the water was immediately taken to the laboratory for testing.

2.3 PROCEDURES

Phase 1 – Settlement of Slurry under self weight

A bakery 'Hobart' mixer was used to mix the samples. The soils were mixed to moisture contents of 233%, 300% and 400%. The initial void ratios (e_o) of the slurried material ranged between 5.14 and 10.04. The Hobart mixer provided a generally homogenous and consistent mix in a controlled condition with minimal sample loss. The mixed slurry suspension was siphoned into the column using a plastic hose placed near the base of the column and this was raised as material filled the column. Standard testing sheets were developed to record relevant data and observations during the testing procedure. Data was recorded during the mixing and dispensing of the slurry. The height of settled soil was recorded at 10 minute intervals up to about 40 minutes, then at 60 minute intervals for 4 hours, then twice daily for the duration of the test.

Measurements were taken at the interface of the settling slurry suspension and clear water above the suspension. The test was continued generally until less than 1 mm to 2 mm of reduction in the height of the settled soil was achieved over two consecutive days.

Some deviations to this general procedure occurred in columns 6 and 13 for the 1000 mm thickness soil samples. Higher rates of settlement of between 3 mm and 16 mm per day were reported in these columns at the completion of the test.

Periodic pH measurements of the water above the slurry were also made using an electronic pH probe calibrated to pH 4 and pH 7 reference solutions on the day of testing.

Phase 2 – Consolidation of slurry under vertical stress

Following completion of the Phase 1 testing, water was siphoned out of the column (taking care not to disturb the settled soil), leaving about 50 mm of water covering the settled soil. The upper sand filter layer was placed over the settled soil. The amount of sand used was weighed and then placed without disturbing the settled soil. The column was carefully filled with water to the top of the column, adding water with as little turbulence as possible. The level between the settled soil and the bottom layer of sand was recorded relative to the base of the column. Phase 2 of the testing commenced with the sample being loaded with a 2 kPa surcharge load. Measurements were taken immediately after the positioning of the surcharge load at time intervals of 6 sec, 15 sec, 30 sec, 1 min, 2 min 15 sec, 4 min, 6 min

15 sec, 9 min, 12 min 15 sec, 16 min, 20 min 15 sec, 25 min then once daily until measurements of less than 1 mm difference in reduction of sample height was recorded over three to eight rounds of monitoring (indicating completion of primary consolidation settlement under the given load increment). Placement of surcharge load weights was continued in this manner until between about 5 kPa to 30 kPa of load was applied to the sample.

For the columns with soil slurry heights of greater than 100 mm (thicknesses generally 300 mm and 1000 mm in this test), completion of >90% primary consolidation was not achieved after several months of monitoring. Even though >90% primary consolidation had not been achieved in these columns, another load increment was added to check that settlement under the given loads was indeed slow and was not due to other factors such as friction. For these columns with thicker soil slurry heights, in all cases it was assessed that >90% primary consolidation had not been achieved even after 6 months to 9 months of testing under the stated loads.

3 RESULTS

3.1 PHASE 1 – SETTLEMENT OF SLURRY UNDER SELF WEIGHT

Settling of the slurry suspension was generally achieved between 0.1 day and 28 days following placement of the soil slurry into the columns. For two columns some higher rates of settlement were reported after 8 days to 35 days of settlement under self weight. A reduction in void ratio of up to 77% was achieved at the completion of the Phase 1 testing.

Table 1: Phase 1 test results.

Sample Number	Sample Diameter (mm)	Before Phase 1 Consolidation					After Phase 1 Consolidation* under self weight				
		Initial Sample Thickness (mm)	Initial M.C.(%)	Initial ρ_w	Initial ρ_d	Initial e_o	Final Sample Thickness (mm)	Final M.C.(%)	Settled ρ_w	Settled ρ_d	Final e_o
Column 1	94	205	400	1.21	0.24	9.24	120	111	1.69	0.80	2.15
Column 2	94	825	300	1.20	0.30	7.39	562	194	1.30	0.44	4.72
Column 3	94	1240	233	1.26	0.33	5.68	968	175	1.33	0.48	4.22
Column 4	94	205	400	1.21	0.24	9.42	97	182	1.44	0.51	3.93
Column 5	94	1290	300	1.20	0.30	7.37	763	164	1.35	0.51	3.95
Column 6	94	1219	233	1.35	0.41	5.20	753	139	1.57	0.66	2.83
Column 7	94	220	400	1.24	0.25	9.14	94	169.6	1.57	0.58	3.33
Column 8	94	820	300	1.24	0.31	7.10	439	151	1.44	0.55	3.34
Column 9	94	1273	233	1.29	0.39	5.52	768	131	1.48	0.64	2.93
Column 10	94	220	400	1.14	0.23	10.04	144	249	1.22	0.35	6.23
Column 11	94	785	300	1.24	0.31	7.11	474	173	1.40	0.51	3.90
Column 12	94	1190	233	1.41	0.42	4.97	1107	217	1.44	0.45	4.56
Column 13	94	1191	233	1.37	0.41	5.14	1120	218	1.39	0.44	4.77
Column 14	94	780	300	1.25	0.31	7.03	585	220	1.34	0.42	5.03
Column 15	94	177	400	1.51	0.30	7.34	127	307	1.71	0.42	4.99
Oedometer 1	46.0	-	68.2	1.61	0.96	1.86	-	-	-	-	-
Oedometer 2	46.5	-	111.2	1.29	0.61	2.77	-	-	-	-	-
Oedometer 3	46.0	-	130.0	1.24	0.54	3.06	-	-	-	-	-
Oedometer 4 (Golder)	50	-	46.6	1.73	1.18	1.21	-	-	-	-	-

- ** - After Phase 1 Consolidation is defined as completion of primary consolidation settlement under self weight. These are slightly different to the values shown for 'Before Phase 2 Consolidation' in Table 2, below.*
- *ρ_w – wet or bulk density, tonnes/m^3. ρ_d – dry density, tonnes/m^3. e_o – void ratio*

A direct correlation between settling time and soil/water content could not be identified from the Phase 1 testing. Correlation of settling time and soil/water content would require a consistent slurry height (say 100 mm) to be used for the 20%, 25% and 30% soil/water ratios.

The pH of the water above the slurry dropped from 6.32 to between about 2.5 and 3.3 within about 5 days to 7 days following placement. This is due to the oxidation of the known Acid Sulfate Soil materials within the estuarine soil.

The implications of this change in pH along with other changes in soil chemistry are beyond the scope of this paper but would need to be addressed for developments where dredging of known Acid Sulfate Soil slurry materials occurs.

Table 1 presents a summary of the results from the Phase 1 Laboratory Testing, along with a comparison of results from Oedometer testing of U_{50} tube field samples taken from the estuarine soil unit.

3.2 PHASE 2 – CONSOLIDATION OF SLURRY UNDER VERTICAL STRESS

For the Phase 2 testing, values of $C_c/(1+e_o)$ ranged between 0.180 and 0.425 and for the oedometer tests the $Cc/(1+e_o)$ values ranged between 0.179 and 0.592. For the Phase 2 testing, values of $C_\alpha/(1+e_o)$ ranged between 0.0069 and 0.0110 and for the odometer tests the values of $C_\alpha/(1+e_o)$ ranged between 0.0067 and 0.0138. It is assessed that a general correlation between column testing and conventional odometer testing can be made.

Meaningful results were only recorded from the 100 mm (approximate) height soil columns. It was found that soil heights greater than 100 mm were continuing to record primary consolidation settlement after 10 months of testing. It is expected that results for soil heights greater that 100 mm may take many years to achieve meaningful results for the Phase 2 testing.

It should also be pointed out that sample thickness does have an influence on the consolidation characteristic of soils as hypothesised by Jamiolkowski *et al.* (1985), and as observed by other researchers in subsequent development of time-dependent models for simultaneous consolidation and creep compression.

Table 2: Results of Phase 2 testing.

Sample Number	Sample Diameter (mm)	Before Phase 2 Consolidation Testing*			After Phase 2 Consolidation Testing			
		Initial Sample Thickness (mm)	Initial Moisture Content (%)	Initial e_o	Final Sample Thickness (mm)	Final e_o	$C_c/(1+e_o)$	$C_\alpha/(1+e_o)$
Column 1	94	120	228.2	5.10	74	2.76	0.425	0.0110 (0.0110 - 0.0053)
Column 4	94	97	181.9	3.93	41	1.08	0.250	0.0093 (0.0012 - 0.0093)
Column 7	94	94	169.6	3.33	64	1.95	0.180	0.0069 (0.0008 - 0.0069)
Oedometer 1	46.0	17.29	68.2	1.86	-	1.05	0.310	0.0067 (0.0012 - 0.0067)
Oedometer 2	46.5	16.15	111.2	2.77	-	1.15	0.566	0.0111 (0.0000 - 0.0111)
Oedometer 3	46.0	16.62	130.0	3.06	-	1.68	0.592	0.0138 (0.0110 - 0.0053)
Oedometer 4 (Golder)	50	-	46.6	1.21	-	0.73	0.179	0.0110 (0.0000 - 0.0138)

- ** - Before Phase 2 Consolidation testing (for the Column tests 1, 4 and 7 only) is defined as after primary consolidation settlement under self weight, placement of sand drainage layer over surface of slurry, addition of a water up to the brim of the 2m high column and immediately after placement of initial concrete weight over the settled soil slurry.*
- *e_o – void ratio*

Plots of thickness of soil (slurry) height versus log time were prepared based on the readings taken during the course of monitoring. Due to space restrictions there is not sufficient room for presentation of these results, however an assessment of the coefficient of vertical consolidation, C_v, was made based on an assessment of t_{50} (the time for completion of 50% primary consolidation) and standard methods contained in AS 1289 6.6.1 (1998). The results for C_v for the 100 mm thick soil height columns displayed some scatter and ranged between 0.06 m^2/year and 30.36 m^2/year, however most results ranged between 0.3 m^2/year and 1 m^2/year.

Table 2 presents a summary of the results from the Phase 2 Laboratory Testing, along with a comparison of results from oedometer testing of U_{50} tube field samples taken from the estuarine soil unit.

Results from Table 2 show that the test methods used seem effective for assessment of $C_c/(1+e_o)$ and $C_\alpha/(1+e_o)$ for materials that are reconstituted and placed at low effective stresses (<30kPa) and high initial void ratios (e_o ranging between 9.14 to 9.42).

Figure 4 plots void ratio versus normal effective stress for the Phase 2 column testing and oedometer test results. The slope of the primary consolidation portion of the oedometer curves appears similar to the slope of the primary consolidation curves for the Phase 1 and 2 column testing. The results for the column testing confirm the absence of pre-consolidation pressure, which is expected for these reconstituted soils. Values of $C_c/(1+e_o)$ and $C_\alpha/(1+e_o)$ appear similar for both test methods where a 100 mm soil thickness for the column testing has been used.

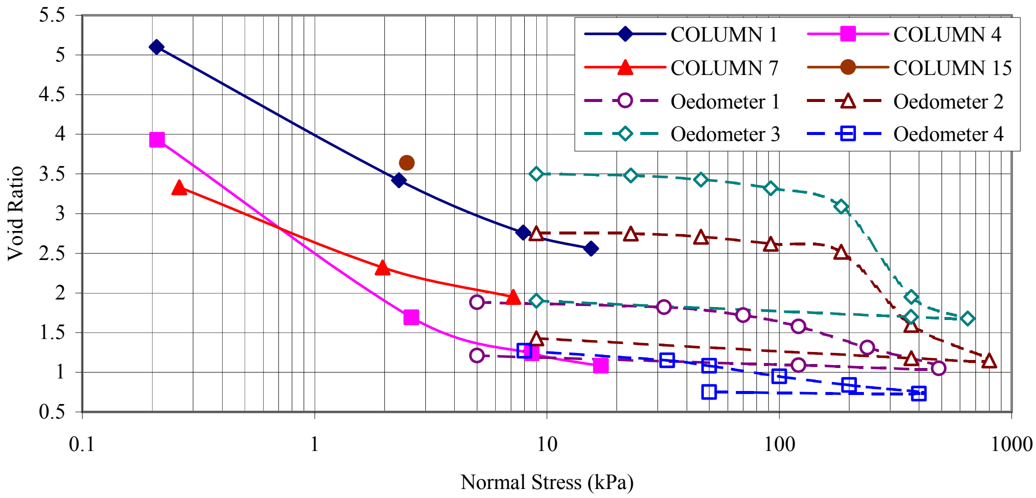

Figure 4: Comparison of Phase 2 column testing results and oedometer testing results for void ratio versus normal effective stress.

4 CONCLUSIONS

The results show the test method adopted for the assessment of settling under self weight and consolidation under load is generally suitable for dredged or reconstituted estuarine type soils in a brackish (somewhat salty) water environment. The test appears suitable for soil thicknesses of about 100 mm. Testing of thicknesses greater than this would require onerous timeframes or a modified testing method. For a 100 mm thickness, results show that a timeframe of 9 months to 12 months would be required for adequate results. Results of thick samples greater than about 100 mm are also likely to be affected by simultaneous primary consolidation and secondary consolidation (creep) behaviour and would require different test methods to provide meaningful results in an economic timeframe.

5 REFERENCES

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