Consolidation Behavior of Cochin Marine Clay under Constant Rate of Strain

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Abstract - The consolidation behaviour of soft clays is of considerable importance in the settlement calculations. The conventional incremental loading consolidation tests are carried out for determining consolidation parameters. Due to the longer duration taken for the conventional incremental loading consolidation tests, nowadays constant rate of strain consolidation (CRS) tests are also used to study the consolidation behavior of clayey soils. CRS tests also are conducted to study the strain rate effect on consolidation. The objective of this study is to compare the consolidation behaviour of Cochin marine clay under incremental and CRS tests. The CRS tests were conducted in an oedometer modified for this purpose. The main parameters investigated are coefficient of consolidation (C_v), Coefficient of compressibility (a_v) and consolidation yield stress (p_c). An attempt has been made to investigate effect of strain rate on consolidation behavior of Cochin marine clay by conducting constant rate of strain (CRS) tests at strain rates 0.12, 0.6 and 3.0 %/minute along with conventional IL tests for comparison. The results indicate that CRS tests with 0.12%/min strain rate gives comparable results with IL tests. Although there are scatters on test data, generally for the strain-rate tested (0.12 – 3%/min), consolidation yielding stress (p_c) increased with strain-rate.

Index Terms – Constant rate of strain consolidation tests, consolidation, Pore water pressure

1 INTRODUCTION

Marine clay is a very soft clayey soil deposited around Indian Peninsula. Marine clay can be located onshore as well. The marine clays are soft clays characterized by low shear strength and high compressibility. Marine clays form one of the important groups of fine grained soils. These soils have high proportions of organic content and are very sensitive to change in the stress system, moisture content and system chemistry of the pore fluid. Due to rapid infrastructure development along the coastal area, lots of civil construction activities take place in marine clays throughout the world. In Cochin most of the areas consist of soft marine clay deposits. The presence of weak marine clays forces the use of expensive deep foundations in these areas. Also, the settlement of foundations is a major problem associated with the structures constructed over these areas.

In geotechnical practice, there are two test methods for determining the consolidation characteristics of clayey soil, namely incremental loading (IL) consolidation test and constant rate of strain (CRS) consolidation test. IL test is more convenient to be conducted and the equipment is relatively simple, and therefore more popular than CRS test in practice. However, the strain rate effect can only be investigated by CRS test. In geotechnical design, for a given clayey soil deposit, it is desirable to know the effect of strain-rate on yielding stress (p_c) and at what strain rate, CRS test can result in the similar result as IL test. In this paper, the results of IL and CRS tests for the undisturbed soil samples are presented and compared.

Various studies have been carried out by researchers on the properties of marine clays worldwide. Cochin marine clay has also been an area of study due to rapid industrialization and fast pace in construction in Cochin area. Studies conducted by Abraham, B. M. et al. (1993) on the strength and compressibility characteristics of Cochin marine clays revealed that the clay deposits are highly compressive with C_c value around 1.5 and natural moisture content very close to liquid limit. It has been observed that almost all the structures, founded on spread footings or raft footings invariably show actual settlement far below the computed values [1].

CRS test has advantages of shorter test duration, continuous measurement of e - p' (e is void ratio and p' is consolidation stress) relationships of a sample, and independent measurement of compressibility and permeability. For the undisturbed Ariake clay it is suggested to use a linear $ln(e) - ln(p')$ relationship in settlement calculation rather than a linear $e - ln(p')$ relationship (Chai, 2006) [2].

It is well known that the consolidation behavior of clayey soils is strain-rate dependent (Leroueil et al., 1985; Tanaka, 2005) and the degree of this dependency is different from soil to soil (Tanaka et al., 2000). Understanding the effect of strain -rate on the consolidation properties is useful for design geotechnical projects, such as excavation and embankment construction, in the regions with soft clayey soil deposit [3] [4] [5].

The dilatancy behavior in constant strain rate of consolidation (CSRC) test indicated that when the stress state entered the normal consolidation region, the state moved to the quasi-elastic state. Since the duration of quasi-elastic state was short in CSRC test, the state did not give a dominant effect to the global behavior of test specimen. Some period of time after the stress state had entered the normally consolidated region, dilatancy tended to occur rapidly with the increase in stress ratio. Since most of the dilatancies had taken place at the earlier stage of consolidation, little dilatancy occurred at the latter stage of the CSRC process. This tendency made the specimen stiffer with the passage of time, and made the

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vertical pressure and pore pressure increase substantially at the last stage of the CSRC process. Considerations to such behavior might be effective to correctly interpret the result of the CSRC test [6].

2. EXPERIMENTAL STUDY

2.1 Location of Sampling

The location of sampling is shown in Fig. 1. Undisturbed soil samples were obtained by Indian standard thin-wall sampler. After the samples were transported into our laboratory, the soil samples were removed from the thin-wall tube, waxed and stored under water. BH-1 is at a depth of about 3 - 5 m.

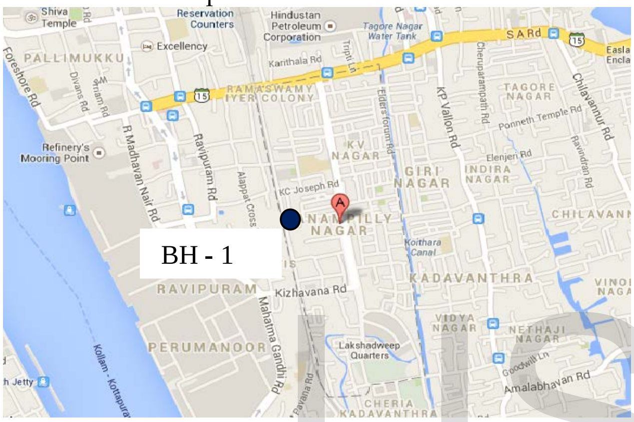

Fig. 1 Bore hole details

2.2 Materials Used

The following materials were used in the experimental study.

2.2.1 Soil

Undisturbed and remolded Cochin marine clay was used for the particular study and it was collected from Panampilly Nagar, Cochin. This soil have liquid limit=79%, plastic limit=25% and clay content of 40%. The soil was classified as 'CH' type. The physical properties of soil were found out as per IS codes are shown in Table 1.

Table 1 Properties of air dried Cochin marine clay

Properties	Values
Liquid limit (%)	79
Plastic limit (%)	25
Shrinkage limit (%)	10
Plasticity index (%)	54
Maximum Dry Density (kN/m^3)	12.94
Optimum Moisture Content (%)	33
Soil classification	CH

3. TEST METHODS

3.1 Incremental loading Consolidation tests

IL consolidation tests were conducted by conventional consolidation device, in which the consolidation pressure is applied by dead load through lever system. The Incremental loading consolidation tests were performed in accordance with IS 2720 Part 15. Air dried soil passing through 425μ sieve and undisturbed soil samples from different depths are used for conducting IL consolidation tests.

Fig. 2 Consolidation apparatus

3.2 Constant rate of strain consolidation tests

Standard triaxial equipment is used to carry out loading of the specimen for the CRS test. Measurement of load, compression and pore pressure are taken continuously. A pore water pressure transducer of 2 bar is used for modifying the oedometer for conducting CRS Consolidation tests. The pore water pressure transducer is shown in Fig.

The set-up of CRS test is illustrated in Fig. 3. Drainage was only allowed at the top surface of the sample and the pore water pressure was measured at the bottom of the sample. A desired strain rate was applied by a motor and gear system from the bottom of the sample. For the device used, the lowest strain rate is 0.12%/min for a sample 20 mm in thickness.

For both IL test and CRS test, the soil samples have a diameter of 60 mm and a nominal height of 20 mm.

CRS tests were carried out according to ASTM D 4186 06. The strain-rates adopted were 0.12%/min, 0.6%/min and 3%/min.

Fig. 3 Triaxial apparatus

Fig. 4 Pore water pressure transducer

4. RESULTS AND DISCUSSIONS

4.1 Coefficient of Consolidation (C_v)

The values of coefficient of consolidation (C_v) from IL and CRS tests for soil sample at 3 – 5 m depth of BH-1 are compared in Fig. 5 to Fig. 7. C_v values from IL tests were determined by √t method (t is time). It can be seen that at low consolidation stress range, CRS tests yielded higher C_v values and after that the C_v values are similar. C_v is a parameter combines the coefficient of hydraulic conductivity (k) and the coefficient of volume change (m_v). The coefficient of consolidation can be found out in CRS test by using following formula,

$$C_v = \frac{rH^2}{a_v u_b}\left[\frac{1}{2} - \frac{b}{r}\left(\frac{1}{12}\right)\right] \quad (1)$$

Where r = strain rate; a_v = coefficient of compressibility; u_b = pore water pressure

Table 2 Values of Coefficient of Consolidation (BH-1, 3m)

Effective Stress kPa	C_v *10^{-2} cm^2/min (BH – 1, 3m)			
	UDS	0.12%/min	0.6%/min	3%/min
4.9	0.024	0.011	0.107	2.914
9.81	0.029	0.273	0.048	1.234
19.61	0.021	0.212	0.043	0.701
39.23	0.092	0.1	0.029	0.342
78.45	0.082	0.09	0.085	0.166
156.91	0.178	0.19	0.4	0.072
313.81	0.081	0.054	0.2	0.095

Table 3 Values of Coefficient of Consolidation (BH-1, 4m)

Effective Stress kPa	C_v *10			

Effective Stress kPa	C_v $*10^{-2}$ cm^2/min (BH – 1, 4m)			
	UDS	0.12%/min	0.6%/min	3%/min
4.9	0.033	1.026	11.843	31.173
9.81	0.020	0.954	4.777	14.490
19.61	0.015	0.052	2.428	6.439
39.23	0.092	0.126	0.905	3.150
78.45	0.185	0.205	0.331	1.546
156.91	0.204	0.186	0.426	0.954
313.81	0.116	0.144	0.229	0.365

Table 4 Values of Coefficient of Consolidation (BH-1, 5m)

Effective Stress kPa	C_v $*10^{-2}$ cm^2/min (BH – 1, 5m)			
	UDS	0.12%/min	0.6%/min	3%/min
4.9	0.038	0.027	3.993	16.072
9.81	0.003	0.038	1.249	5.001
19.61	0.053	0.05	0.988	2.403
39.23	0.580	0.874	0.191	0.971
78.45	2.894	1.988	0.072	3.255
156.91	2.239	2.22	2.256	4.725
313.81	1.981	1.797	2.235	2.211

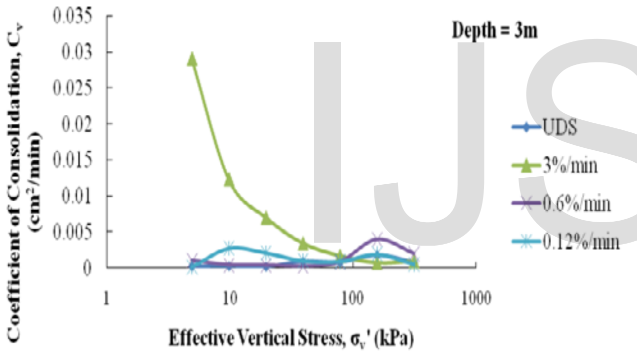

Fig. 5 C_v-Stress-Strain rate relation

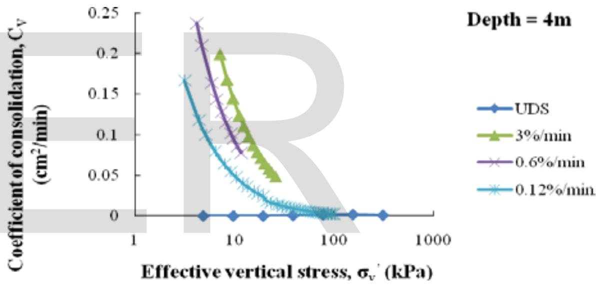

Fig. 6 C_v-Stress-Strain rate relation

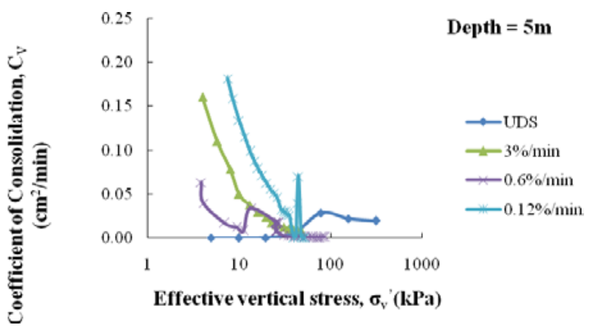

Fig. 7 C_v-Stress-Strain rate relation

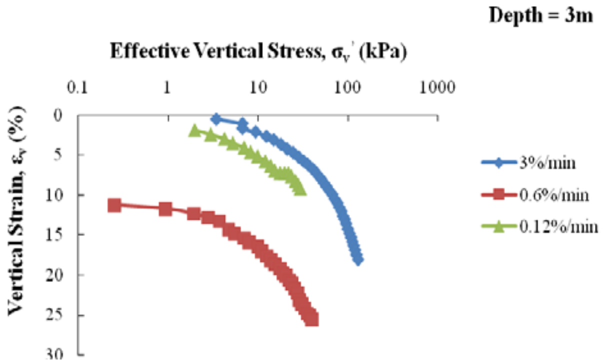

Fig. 8 Stress-Strain Strain Rate relation

4.2 Coefficient of compressibility (a_v)

The coefficient of compressibility (a_v) is defined as the decrease in void ratio per unit decrease in effective stress. It is equal to the slope of void ratio – pressure curve at the point under consolidation in conventional consolidation test. In CRS test the coefficient of compressibility is obtained from the following formula,

$$a_v = \frac{C_c}{2.3\overline{\sigma_1'}} \qquad (2)$$

Where C_c = compression index; σ_1'= average vertical effective stress.

From the test results the coefficient of compressibility got decreased with increase of depth from 3 to 5m. The coefficient of compressibility also decreased from 0.302 - 0.179 cm²/kg with increase of applied pressure from 0.5 to 3.2kg/cm² for 3m depth. The coefficient of compressibility decreased from 0.286 to 0.213 cm²/kg and 0.278 to 0.157 cm²/kg, corresponding to 4 and 5m respectively. The coefficient of compressibility obtained from CRS test is also decreasing with increase of effective stress. The CRS test conducted with 0.12%/min gives comparable results with IL test.

4.3 Consolidation Yielding Stress (p_c)

Figure 8 shows the comparison of consolidation yielding stress at BH-1 (see Fig.1 for location). Although the data show certain scatter, generally it can be observed that: (1) p_c values for the strain-rate of 3%/min are higher than that of strain-rate of 0.12%/min. It is considered that the scatter was mainly caused by the non-uniformity of the undisturbed samples used.

Table 5 Yield stress for consolidation

Depth (m)	Strain rate (%/min)	Yield stress for consolidation (kPa)
3	0.12	15
	0.6	30
	3	80
4	0.12	8
	0.6	10
	3	20
5	0.12	8
	0.6	10
	3	12

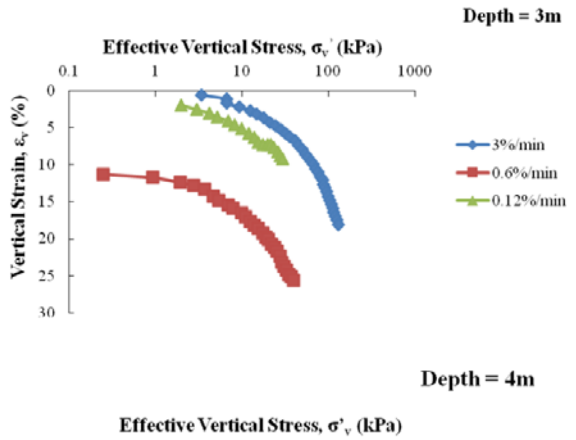

Fig. 9 Stress-Strain Strain Rate relation

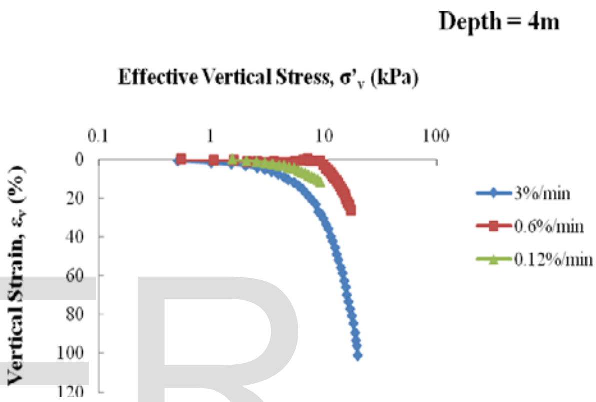

Fig.10 Stress-Strain Strain Rate relation

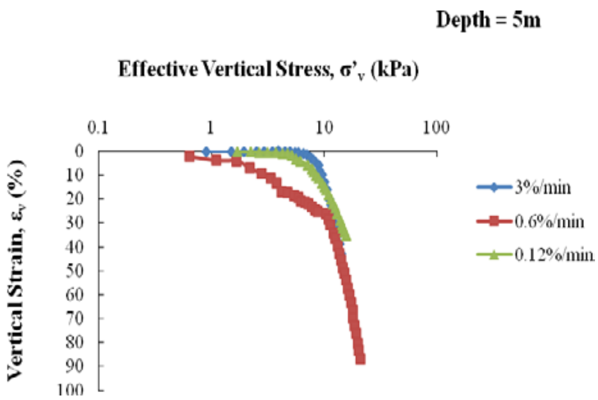

Fig. 11 Stress-Strain Strain Rate relation

5. CONCLUSIONS

The index properties of Cochin marine clay were found out and are classified as CH.

The results of incremental loading (IL) consolidation tests and constant rate of strain (CRS) consolidation tests for the soil samples in Cochin, have been presented, compared and discussed. Based on the test and analysis results, the following conclusions can be drawn.

1. Coefficients of consolidation (C_v): Although C_v values from IL and CRS tests are comparable. C_v obtained from IL test ranges from 0.024 – 0.081 × 10^{-2}cm^2/min and for CRS test corresponding to 0.12%/min is 0.011 – 0.054 × 10^2cm^2/min for 3m depth. The C_v obtained from IL test ranges from 0.033 – 0.116 × 10^{-2}cm^2/min and 0.038 – 1.981 × 10^{-2}cm^2/min for 4 and 5m respectively.
2. The coefficient of compressibility (a_v) decreases as the depth increases. Also the coefficient of compressibility decreases with increase of applied pressure.
3. Consolidation yielding stress (p_c): Although there are scatters, generally, for the strain-rate tested (0.12 – 3%/min), p_c increases with strain-rate.

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