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EFFECT OF TEST CONDITIONS ON THE CONSOLIDATION BEHAVIOUR OF A CLAY USING RECTANGULAR HYPERBOLA METHOD

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SYNOPSIS

Terzaghi's one dimensional consolidation theory has been used widely to evaluate coefficient of consolidation, C_v. This paper examines the effect of sample thickness, drainage conditions (one and two ways) and preconsolidation pressure on the coefficient of consolidation, e-log p behavior and secondary compression coefficient. To bring out the effect of preconsolidation pressure (P_c), the results of a sample having P_c of 100 kPa was compared with that of a normally consolidated sample. Experimental results reveal that sample thickness does not have much effect on e-log p behavior, coefficient of consolidation, and on the secondary compression coefficient. Coefficient of consolidation determined by the rectangular hyperbola method for the percent consolidation range of 60% to 90% is fairly constant for all the pressure increments considered. The time, t versus compression (δ) data was plotted in a convenient form between t/H^2 vs $[(t/H^2) \times (H/\delta)]$ to take care of the thickness, (H) effect resulting in a straight line plot which made the analysis easier. One way drainage has shown higher coefficient of consolidation than that of two way drainage condition. Preconsolidated samples have shown higher C_v values than normally consolidated samples. The secondary compression coefficient was found to be increasing with pressure for all the specimens tested.

INTRODUCTION

Terzaghi's one-dimensional consolidation theory is widely used to evaluate the rate of settlements with acceptable accuracy for various field conditions. One-dimensional consolidation tests are commonly used for the measurement of coefficient of consolidation, C_v and coefficient of volume change, m_v for clayey soils. Laboratory measured C_v values depends on various factors such as load increment ratio, duration, sample thickness, temperature and drainage conditions. Leonards and Girault (1961) showed that by adopting large load increment ratios, the rate of excess pore water pressure dissipation can be reliably predicted from Terzaghi's theory. With regards to time consolidation data, it has been shown by Newland and Allely (1960) that the effect of sample thickness was found to essentially agree with the Terzaghi's theory of consolidation. The increase in the sample thickness in-

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creases the total compression undergone by the specimen and the resulting time-compression curves were similar in shape but displaced with time. (Aboshi, 1973). Drainage is an another important factor which affects the consolidation test results.

Several methods have been proposed for obtaining a reliable value of C_v from laboratory oedometer tests. The usual technique is to compare some characteristic features of the theoretical time factor (T_v) and the degree of consolidation (U) relationship with the time-compression data obtained in the laboratory. The curve fitting procedure forms the basis for most of the graphical techniques available in the literature.

The rectangular hyperbola method (Sridharan & Rao 1981, Sridharan & Prakash 1985 and Sridharan et al 1987) is a versatile method for determination of coefficient of consolidation. This method works for all types of time-compression curves and is based on the fact that the theoretical time factor (T_v) and degree of consolidation (U) forms a rectangular hyperbola over a range of 60% to 90% of degree of consolidation. Similarities between theoretical T_v/U vs T_v and experimental t/δ vs t plot were used to develop this method. The advantage of using 60% to 90% consolidation data eliminates the effects of initial sample disturbance and of secondary compression.

In spite of several contributions in consolidation testing, the results of systematic investigations on the effect of variation in sample thickness and different drainage conditions on the compressibility and coefficient of consolidation are small. This paper reports the results and their analysis of one-dimensional consolidation tests carried out using three different thicknesses under one-way and two-way drainage conditions. Tests have been conducted using fixed ring as well as floating ring devices. One test specimen was preloaded to 100 kPa to bring out the effect of precompression on the coefficient of consolidation and secondary compression coefficient.

MATERIALS AND METHODS

Sample collection

Samples were collected from Parur site located 25 km from the Cochin airport in the Kerala State of India. Boreholes were made by the shell and auger method at selected locations to determine the soil profile and to collect representative samples for laboratory work. Casing pipes were driven to protect the sides. Representative samples were collected in 100 mm diameter thin stainless steel sampling tubes from 150 mm diameter boreholes. Sufficient quantities of representative samples were collected in polythene bags and sealed immediately to avoid pore fluid loss. The various representative samples were later thorougly mixed and stored in air tight polythene bins taking precaution to avoid moisture loss.

Methods

Three standard fixed ring consolidometers (supplied by Wykhamfarance & Co) were used to carry out simultaneous consolidation tests. Stainless steel rings of different heights of 14 mm, 20 mm, and 25 mm and with the same inside diameter of 76 mm were specially made for use in the tests. The inner surface of the rings was coated with silicon grease to minimise side friction between the rings and the clay soil. The representative soil with natural field moisture content of 105% and liquid limit of 117% was added with extra water to reach a water content of 140%, and thoroughly mixed using a mechanical mixer. The higher moisture content was chosen to remove any field prestress effects. For each series of prepared samples fresh soil was used from the bulk sample.

The representative soil with water content of 140% was well mixed and hand remoulded into the consolidation rings of required height (14 mm or 20 mm or 25 mm). The rings were attached with an adapter of 5 mm to increase its height and the soil was hand remoulded to the increased height. Care was taken to hand remould the samples uniformly. Reproducibility tests carried out twice, indicated that variations were neglegible.

The remoulded sample was deaired for entrapped air bubbles using a vacuum dessicator containing distilled water. The adapter was removed carefully and the sample was then trimmed to the thickness equal to the height of the ring (14 mm or 20 mm or 25 mm) and placed into the consolidometer. The tests were performed in a room maintained at an uniform temperature of 20 ± 2°C. After preparing the samples, they were placed into the consolidation cell and oedometer.

Several series of experiments were conducted using the fixed ring consolidometers; (i) double drainage tests where drainage from both top and bottom of the specimen was allowed and (ii) single drainage tests where drainage only from top of the specimen was allowed. In the "double drainage" series, porous stones were placed both at top and bottom of the specimen with filter papers in between the soil specimens and the porous stone. For the single drainage series, a perspex plate of 8 mm thickness was fixed at the bottom of the ring and sealed allround. For the test series on "floating ring" both top and bottom porous stone had a diameter of 74 mm, slightly less than the ring diameter of 76 mm and can freely move inside the ring. Fig. 1 shows the various arrangements for "single drainage", "double drainage" and "floating ring" tests.

Samples were loaded gradually starting with a seating load of 1.56 kPa with load increments equal to load increment ratio of 1. Thus the various increments were 1.56, 3.125, 6.25, 12.5, 25, 50, 100, 200 and 400 kPa. To bring out the preconsolidation effect, one sample was loaded gradually to 100 kPa (Load increment ratio = 1) unloaded to 6.25 kPa and reloaded to 400 kPa.

Time-compression readings were taken at regular intervals (e.g. 10 sec, 30 sec, 45 sec, 1 min, 2.25 min, 4 min, 6.25 min, 9 min, 12.25 min, 16 min, ...). The duration of each load increment was kept to a minimum of 1 day for 14 mm thick samples and with two way drainage and a minimum of 4 days for 25 mm thick samples with one way drainage. The duration of each load increment was sufficient to allow secondary compression.

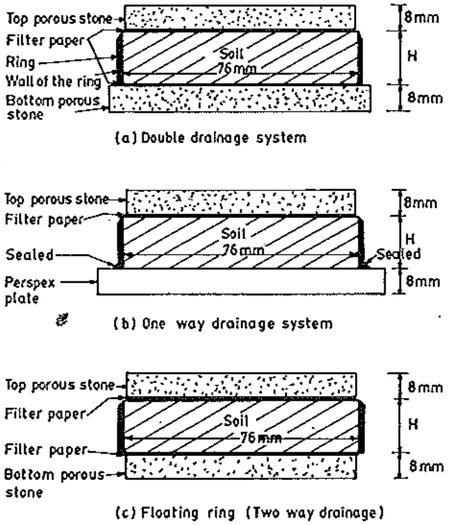


Fig. 1 Arrangements for different drainage conditions.

RESULTS AND DISCUSSION

The basic properties of the soil used in the present investigation are presented in Table 1. Fig. 2 shows typical variation of % strain with t/H^2 (where t is the time and H is the length of the drainage path at the beginning of the load increment) for a pressure range of 100 kPa to 200 kPa for both drainage conditions. The time-compression curves were drawn separately for different thicknesses and the immediate compression was determined by Casagrande method (Taylor, 1948). Fig. 2 shows the time-compression behavior (devoid of initial compression) for samples having various thicknesses. By this procedure, it is possible to compare the time-compression results of various thicknesses. Similar results have been obtained for other pressure increments. In spite of two fold variation in thickness, the experimental points lie along a unique line up to about 80% of consolidation. The results suggest that sample thickness has a negligible effect on Casagrande's t versus δ relationship.

Table 1 Index properties of the soil studied.

Field water content	105%
Remolding Water Content	140%
Specific gravity	2.76%
Liquid limit	117%
Plastic limit	35.4%
Plasticity Index	81.6%
Shrinkage limit	23.3%
Clay size	52%
Silt	23%
Sand	25%

For clarity, the results of one-way and two-way drainage conditions are plotted separately. The inset of Fig. 2 represents the mean line of different thicknesses for single and double drainage conditions. At lower t/H^2 ratio single drainage has shown slightly higher δ/H values and at higher values of t/H^2, double drainage and single drainage lines merge. Single drainage gives larger values of % strain or larger change in void ratio at any t/H^2 value and the difference almost vanishes at large t/H^2 value.

Sridharan and Rao (1981), Sridharan and Prakash (1985), Sridharan et al (1987) have shown that Terzaghi's Time Factor - % consolidation relationship and experimental t-δ relationship behaves as a rectangular hyperbola for the range of 60% to 90% consolidation. Following the above conclusion the plot of t/H^2 vs $(t/H^2 \times H/\delta)$ relationship should give a straight line. Further, C_v could be calculated from the slope and intercept as : (Sridharan, Murthy and Prakash, 1987)

$$C_v = (0.24\, m_1)/C_1 \quad \text{......} \quad \text{(i)}$$

where m_1 is the slope and C_1 is the intercept of t/H^2 vs $(t/H^2 \times H/\delta)$ plot.

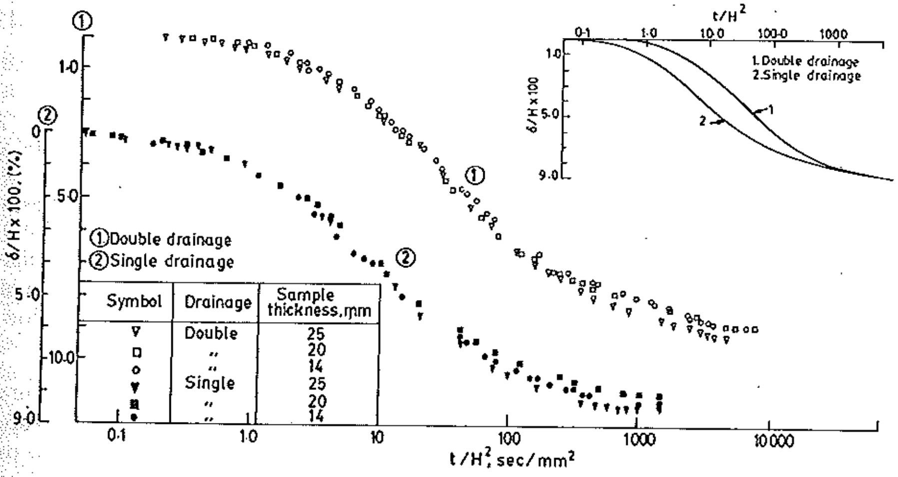


Fig. 2 Variation of % strain with t/H^2.

The t/H^2 vs $(t/H^2 \times H/\delta)$ relationship for different thicknesses and for one-way and two-way drainage conditions, respectively for the test results in the range of 60% to 90% consolidation was examined. Figs. 3a and 3b represents the variation of t/H^2 vs $(t/H^2 \times H/\delta)$ for one-way and two-way drainage conditions respectively for a pressure range of 100 kPa-200 kPa. The line shown represent the best fit line for the three different thicknesses. It can be seen that although a good correlation exists [$r = 0.9985$ for double drainage and $r = 0.9585$ for single drainage] between t/H^2 and $(t/H^2 \times H/\delta)$, the scatter of points is more for one way drinage. Between 60% to 90% consolidation the effect of thickness on δ-t behavior is negligible.

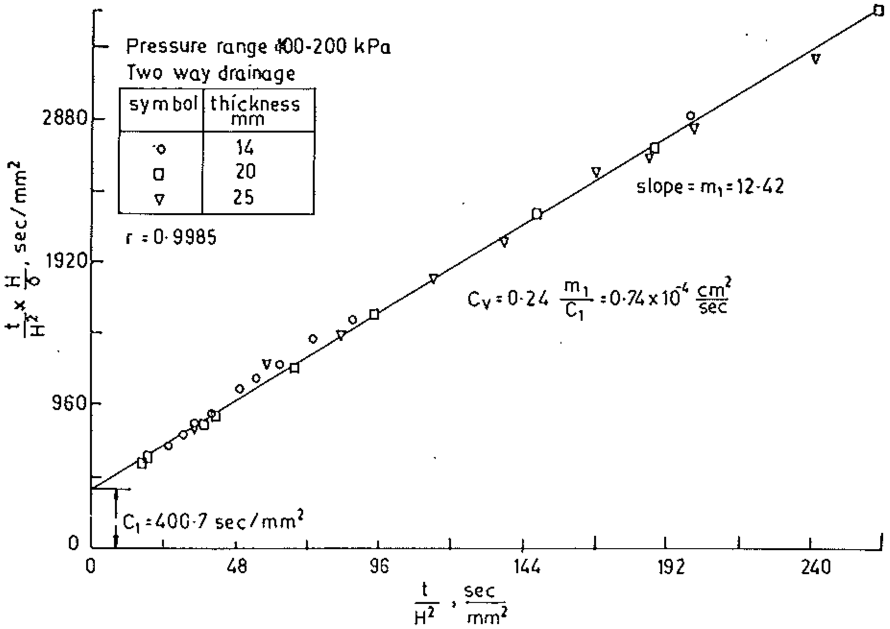


Fig. 3a Variation of t/H^2 with $t/H^2 \times H/\delta$ for two way drainage conditions.

Fig. 4a represents the variation of t/H^2 vs $(t/H^2 \times H/\delta)$ for two way drainage condition for different pressure increments. For clarity the experimental points are not shown. Each line represents the best fit for different thicknesses for a particular pressure increment considered. The lines for different pressure increments have fallen in a narrow band. The mean line of all pressure increments is having a correlation coefficient of 0.987.

Fig. 4b represents the variation of t/H^2 vs $(t/H^2 \times H/\delta)$ for all the pressure increments for one way drainage condition. The best fit line for each pressure increment have shown a correlation coefficient, of more than 0.94. The mean line of all the individual lines is also shown in the figure, which has a correlation coefficient of 0.983. In both these Figures (4a and 4b), the time-compression data, devoid of initial compression and data points between 60% and 90% consolidation have been used. This has been done intentionally because in the rectangular hyperbola method (Sridharan and Rao, 1981, Sridharan et al 1987) the plot of T_v vs T_v/U between 60% and 90% consolidation is essentially linear. Thus the coefficient of consolidation for the average line was calculated using 60%-90% consolidation data and is tabulated in Figs. 4a and 4b.

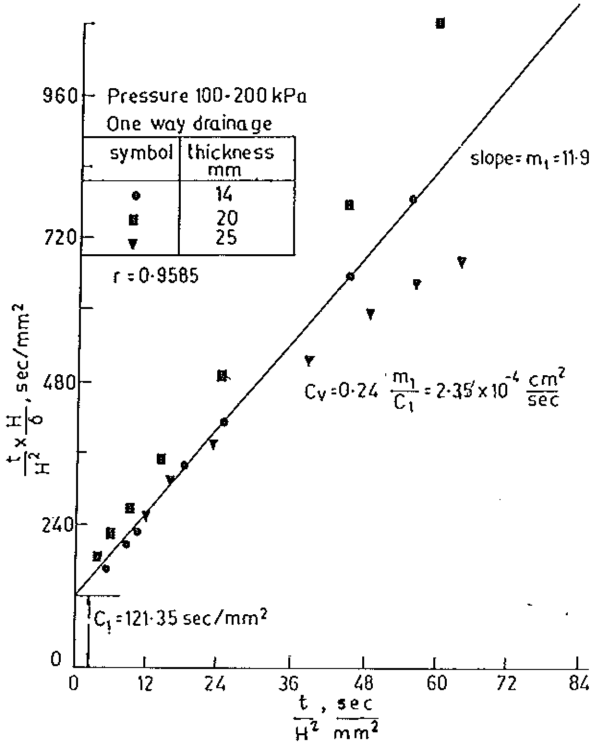
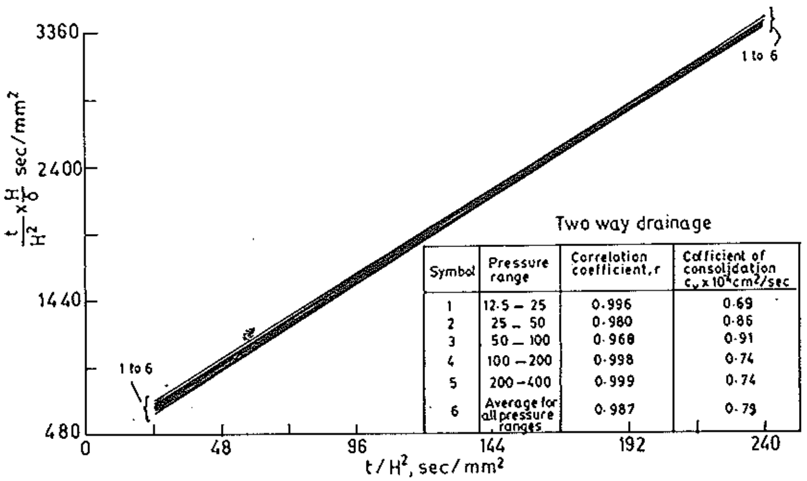


Fig. 3b Variation of t/H^2 with $t/H^2 \times H/\delta$ for one way drainage conditions.

Unlike what is observed for the two way drainage condition, different lines are obtained for different pressure increments for one way drainage conditions (Fig. 4b). The coefficient of consolidation generally increases with increase in pressure increment. This may be attributed to the increase in pressure gradients with increase in pressure increment. It should be noted that the increase in pressure increment is doubled for each increment to keep the load increment ratio of 1. Except for one value (i.e. $C_v = 2.35 \times 10^{-1}$ cm²/sec. for the pressure increment of 100-200 kPa, Fig. 4b), the results for the coefficient of consolidation range from 1.00 to 1.75×10^{-4} cm²/sec. The overall mean value is 1.56×10^{-4} cm²/sec. Considering the various



Symbol	Pressure range	Correlation coefficient, r	Cofficient of consolidation $c_v \times 10^{-4}$ cm²/sec
1	12·5 – 25	0·996	0·69
2	25 – 50	0·980	0·86
3	50 – 100	0·968	0·91
4	100 – 200	0·998	0·74
5	200 – 400	0·999	0·74
6	Average for all pressure ranges	0·987	0·79

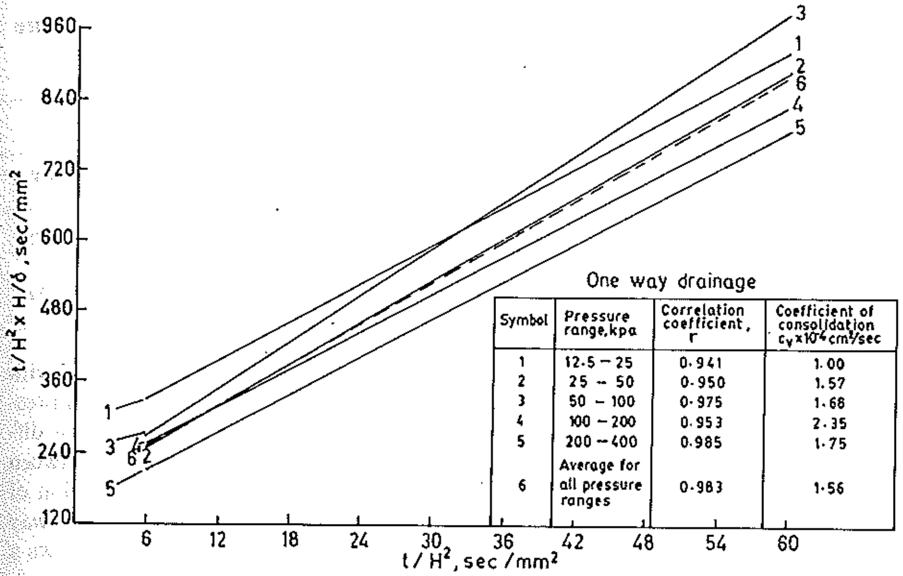
Fig. 4a **Variation of t/H^2 with $t/H^2 \times H/\delta$ for two way drainage condition for different pressure increments.**

factors involved viz different pressure increments and different thicknesses, the variation in C_v can be considered as marginal for the one-way drainage condition. For the two way drainage condition (Fig. 4a) the variation in C_c is lower (0.69×10^{-4} cm²/sec. to 0.91×10^{-4} cm²/sec).

The results indicate that C_v values for one-way drainage are almost twice that of the two way drainage condition. The authors do not advance any specific reason to explain this other than differences in the drainage conditions. This requires further verification to obtain additional results using different soils. In order to further clarify this point, some limited results were analysed using the conventional δ-$\sqrt{t}$ (Taylor's method) and δ-logt (Casagrande's method). Table 2 shows the results. It can be seen that the C_v values obtained from one way drainage is more than the two way drainage condition and it is more than two fold, thus corroborating the results obtained using the rectangular hyperbola method. The C_v obtained by δ-$\sqrt{t}$ method is from t_{90}, δ-logt method from t_{50} and the rectangular hyperbola method uses the data obtained from 60% to 90% consolidation.

The effect of thickness is more significant for one way drainage than two way drainage condition. Newland and Allely (1960) conclude that C_v is independent of sample thickness. Only one test result is available in their paper with regard to the drainage condition on C_v which agrees well with the results reported here.

The coefficient of secondary compression per log cycle was calculated using equation (ii) (Sridharan and Rao 1982) using δ-logt curve. For this purpose the δ_{100} point was identified in the conventional way (Taylor, 1948), beyond which the straight line portion was identified in the δ-logt plot.



Symbol	Pressure range, kpa	Correlation coefficient, r	Coefficient of consolidation $c_v \times 10^{-4}$ cm²/sec
1	12·5 – 25	0·941	1.00
2	25 – 50	0·950	1.57
3	50 – 100	0·975	1·68
4	100 – 200	0·953	2·35
5	200 – 400	0·985	1·75
6	Average for all pressure ranges	0·983	1·56

Fig. 4b **Variation of t/H^2 with $t/H^2 \times H/\delta$ for one way drainage condition for different pressure increments.**

Table 2 **Comparison of Coefficient of Consolidation obtained from different drainage conditions.**

Method	Coefficient of Consolidation Values × 10^{-4} cm²/sec					
	One-way Drainage			Double Drainage		
	H = 20 mm Pr : 50-100 kPa	H = 20 mm Pr : 100-200 kPa	H = 14 mm Pr : 50-100 kPa	H = 20 mm Pr : 50-100 kPa	H = 20 mm Pr : 100-200 kPa	H = 14 mm Pr : 50-100 kPa
δ-logt (Casagrande's)	2.90	2.32	2.69	1.05	0.93	0.95
δ-$\sqrt{t}$ (Taylor's)	2.79	2.39	2.59	0.98	1.03	0.72

$$C_{\alpha\epsilon} = (\Delta S/\Delta \log t)/H_f \qquad \text{.........} \quad \text{(ii)}$$

Where $C_{\alpha\epsilon}$ = Coefficient of secondary compression $\Delta S/\Delta \log t$ = Slope of the secondary compression part of the time-compression curve on the δ-logt plot H_f = Height of the specimen at the end of each load increment.

Table 3 Variation of Coefficient of Consolidation $C_v \times 10^{-4}$ cm²/min with pressure increments for over and normally consolidated samples.

Sl No	Soil Description	Pressure increment, kPa					
		6.25-12.5	12.5-25	25-40	50-100	100-200	200-400
1	Over consolidates sample P_c = 100 kPa	4.26	1.80	1.11	2.75	0.96	0.52
2	Normally consolidated sample	0.43	0.71	0.47	0.51	0.84	0.79

Figs. 5a and 5b present the variation of secondary compression coefficient with pressure. The secondary compression coefficient increases with the increase in pressure for all the sample thicknesses. Fig. 5a and 5b also compare the results of different thicknesses. No significant variation or definite trend is observed between samples having various thicknesses. Fig. 5c compares the mean line of variation of coefficient of secondary compression with pressure for one way and two way drainage conditions. The rsults indicate that one way drainage condition shows a

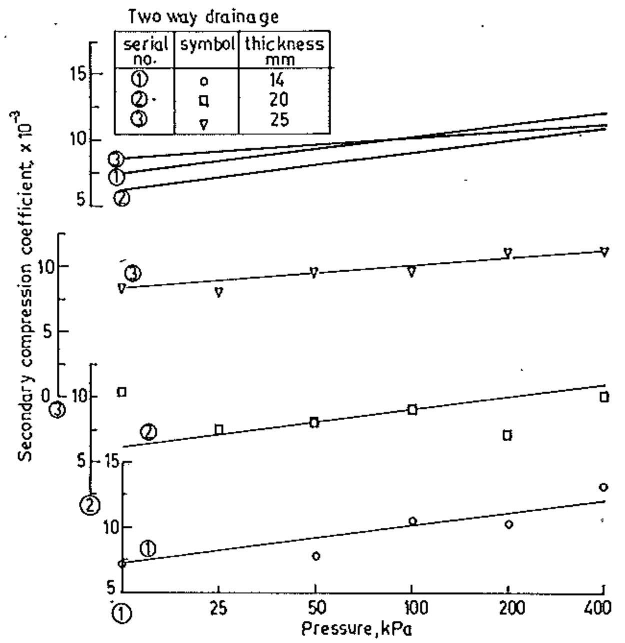


Fig. 5a Variation of coefficient of secondary compression with pressure for two way drainage conditions.

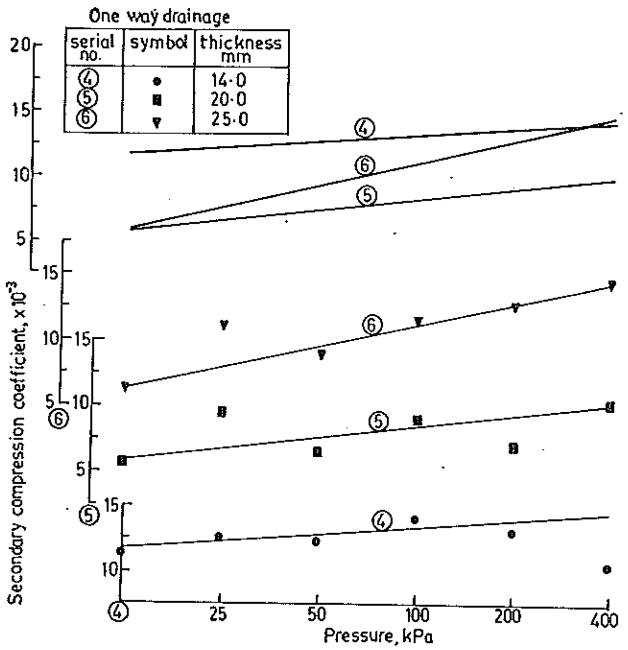


Fig. 5b Variation of coefficient of secondary compression with pressure for one way drainage conditions.

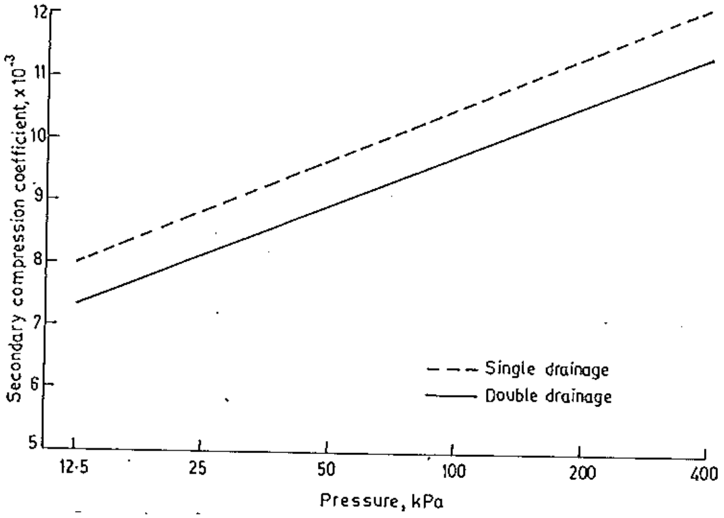


Fig. 5c Comparison of variation of coefficient of secondary compression with pressure for one way and two way drainage conditions.

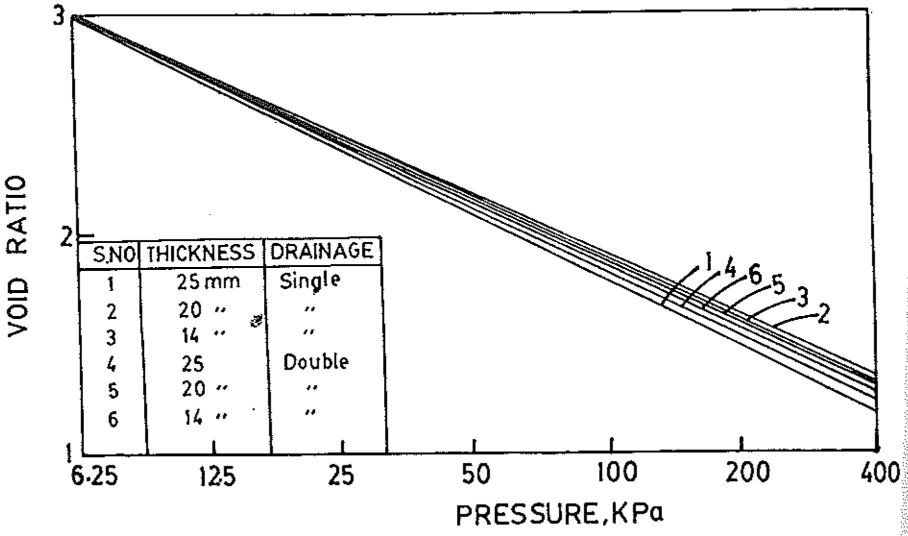


Fig. 6 e-log p behavior of different specimens studied.

higher coefficient of secondary compression, although it is negligible when compared to the variation due to pressure increment. These results agree with results reported by Gray (1963) and Sridharan and Rao (1982).

Fig. 6 plots the e-log p behavior of the specimens with different thicknesses and drainage conditions studied. For clarity only lines have been shown without experimental points. The void ratio at the nominal load of 6.25 kPa is taken as the average void ratio of the specimens. The maximum variation in the initial void ratios of various samples is of the order of ± 0.05. The e-log p behaviour of all the specimens tested is essentially the same which suggests that thickness and drainage path have a negligible effect on the e-log p behavior.

Fig. 7 plots t/H^2 vs δ/H for the results obtained using floating ring and fixed ring device for a pressure range of 100 kPa - 200 kPa as typical results. Similar results have been obtained for other pressure ranges. The results obtained have shown that the floating ring gives slightly higher δ/H values for all the presssure ranges. Fig. 8 compares the e-log p behavior. The equilibrium void ratio obtained using the floating ring device show slightly lower values than fixed ring. This is presumably due to the larger compression by the soil specimen in floating ring device under each load increment in comparison to fixed ring device. The t/H^2 vs $(t/H^2 \times H/\delta)$ plot of the results between 60% to 90% consolidation is presented in Fig. 9 using both fixed and floating ring. The results of both fixed and floating ring tests lie on a straight line

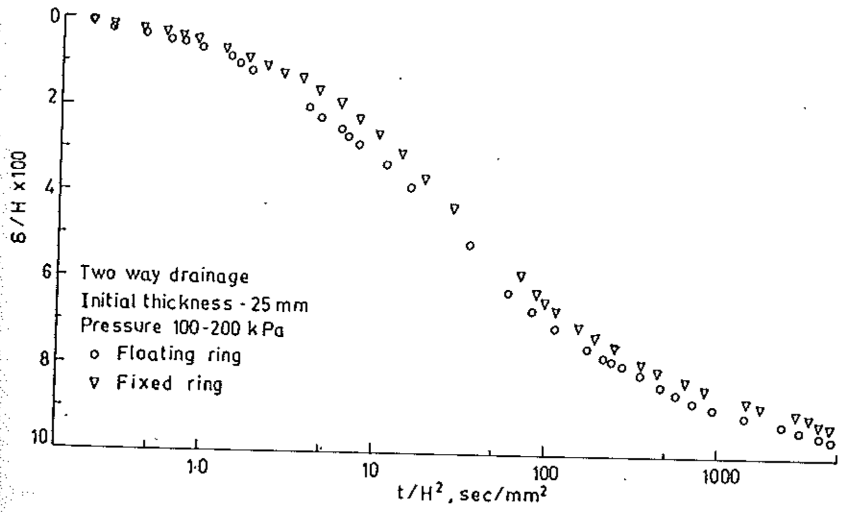


Fig. 7 Variation of δ/H with t/H^2 obtained using floating ring and fixed ring device.

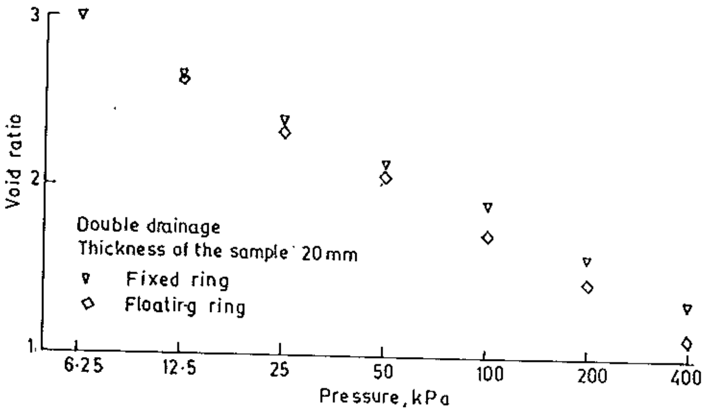


Fig. 8 Variation of $t/H^2 \times H/\delta$ with t/H^2 obtained using floating ring and fixed ring device.

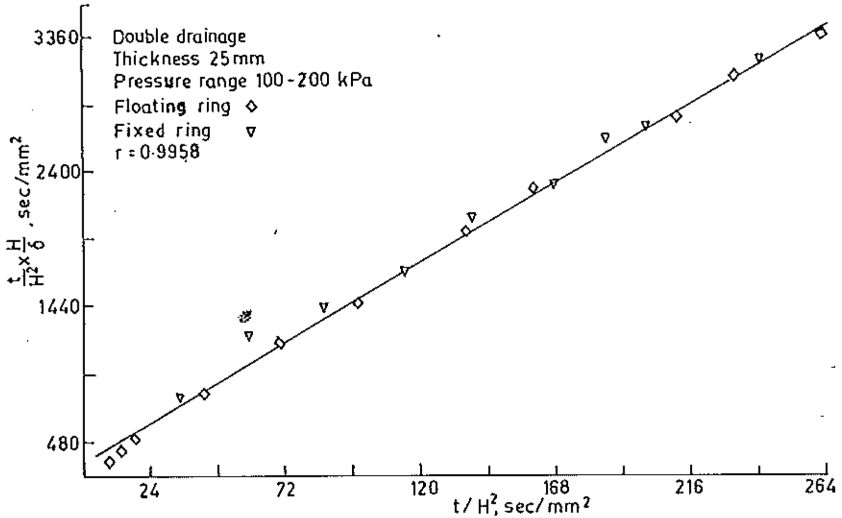


Fig. 9 Comparison of e-log p behavior obtained using fixed ring and floating ring device.

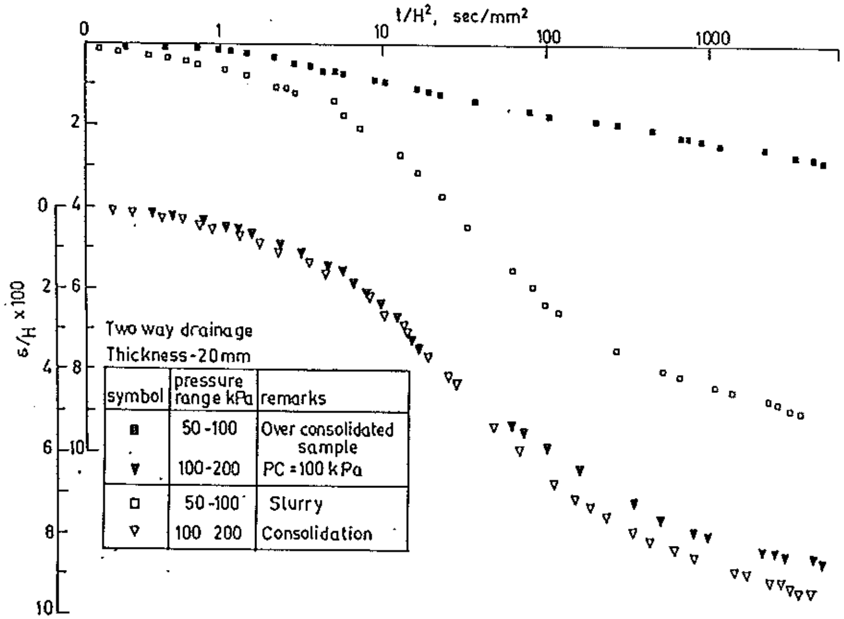


Fig. 10 Comparison of % strain with t/H^2 for normally consolidated and over consolidated sample.

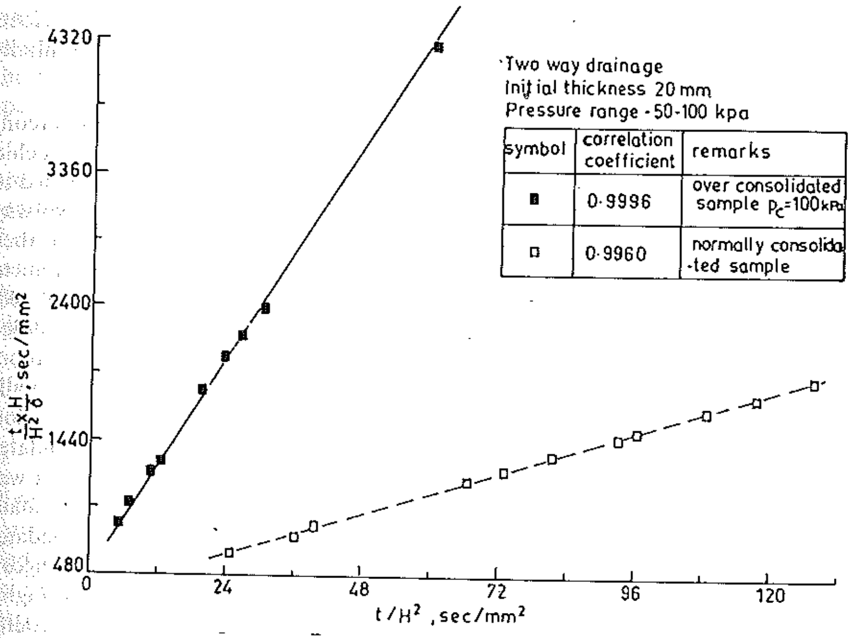


Fig. 11a Comparison of variation of $t/H^2 \times H/\delta$ with t/H^2 for over consolidated and normally consolidated samples for a pressure range of 50 kPa - 100 kPa.

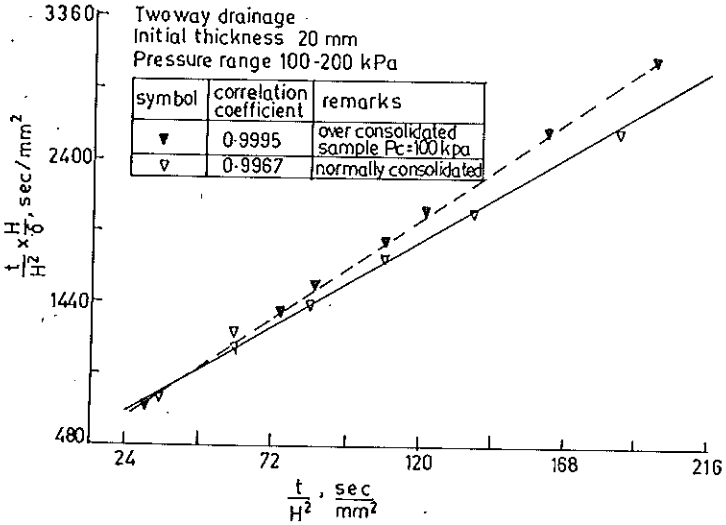


Fig. 11b Comparison of variation of $t/H^2 \times H/\delta$ with t/H^2 for over consolidated and normally consolidated samples for a pressure range of 100 kPa - 200 kPa.

that has a correlation coefficient of 0.9959. These results suggest that the coefficients of consolidation obtained using floating ring and fixed ring devices are essentially the same.

To study the variation of coefficient of consolidation between overconsolidated and normally consolidated soils, specimens of 20.9 mm thick of Cochin marine clay (Table 1) were remolded at 140% water content and gradually loaded to 6.25 kPa in a standard consolidation apparatus of fixed ring type under two way drainage. They were further loaded to 100 kPa with a load increment ratio = 1, then unloaded to 6.25 kPa and further reloaded to 400 kPa with the same load increment ratio. The time-compression results for pressure ranges (50-100) kPa and (100-200) kPa are presented in Fig. 10 and the results of both normally and overconsolidated specimens are compared. For a pressure range of 50 kPa-100 kPa, the overconsolidated specimen has shown much lesser δ/H values in comparison to normally consolidated sample as one would expect. For the same samples, δ/H vs t/H^2 plots for a pressure range of 100 kPa-200 kPa shows the results of over consolidated specimen lying very close to that of normally consolidated specimen in such a way that δ/H values of over consolidated specimen is slightly lower than that of normally consolidated specimen and tending towards the results of normally consolidated specimen. The t/H^2 vs $(t/H^2 \times H/\delta)$ plots of the results for the same pressure ranges is shown in Fig. 11a and Fig. 11b. Fig. 11a shows that overconsolidated soil has higher slope than the normally consolidated sample which suggests a higher coefficient of consolidation for overconsolidated specimens. Table 3 shows the C_v values calculated from t/H^2 vs $(t/H^2 \times H/\delta)$ plots for overconsolidated and normally consolidated specimens. The C_v for overconsolidated specimens up to 100 kPa is much higher than that of normally consolidated sample and beyond this pressure the C_v of over consolidated specimen is close to that of normally consolidated specimen.

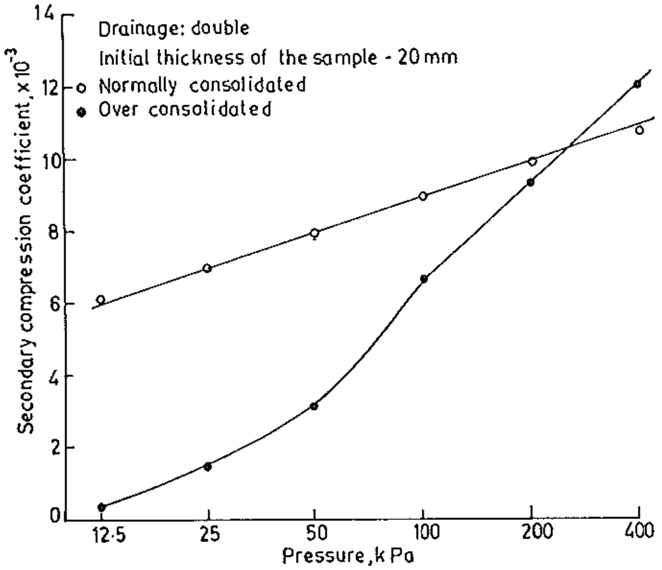


Fig. 12 **Variation of secondary compression with pressure for over consolidated and normally consolidated specimens.**

Fig. 12 compares the variation of secondary compression coefficient with presssure for normally and overconsolidated (P_c = 100 kPa) specimens. The secondary compression coefficients of the over consolidated sample at stresses below the preconsolidation pressure are much less than the values for the normally consolidated sample. At stresses greater than the pre-consolidation pressure the secondary compression coefficient of over consolidated specimens tends to merge with those of the normally consolidated soil.

CONCLUSIONS

The e-log p behavior is essentially same for all the specimens tested irrespective of two fold variation in their sample thicknesses and variations in drainage conditions (one way or two way) and the type of consolidation ring (fixed or floating) used. The t/H^2 vs $t/H^2 \times H/\delta$ plot between 60% and 90% consolidation results in a unique stright line irrespective of different thicknesses of specimens and for all pressure increments suggesting that the variation in C_v can be considered as negligible for different pressure ranges and thicknesses of specimen. However, samples with one way drainage conditions have shown higher coefficients of consolidation by a factor of about two than with two way drainage conditions. A comparison of results obtained using floating ring device and fixed ring device indicates that while the coefficient of consolidation is essentially the same, compression obtained to be marginally more for floating ring device. Secondary compression increased with pressure for all the specimens tested and no definite trend was observed in secondary compression between samples of different thicknesses. One way drainage has shown marginally larger coefficient of secondary compression than two way drainage system. Overconsolidated specimens had higher coefficients of consolidation than normally consolidated specimens at the same pressure increment. Stress history effects had little influence at stresses greater than the preconsolidation pressure. Also over consolidated specimens show less secondary compression than normally consolidated specimen for pressures less than the preconsolidation pressure. Beyond preconsolidation pressure, secondary compression of normally consolidated and over consolidated specimens are essentially same.

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