Secondary Consolidation and the effect of Surcharge Load

Thuvaragasingam Bagavasingam
University of Moratuwa
Colombo, Sri Lanka

***Abstract*— This paper analyses the behavior of soft clays during consolidation process. The difference in rate of consolidation between primary and secondary is identified by Oedometer test as per the Buisman's model. Peat sample taken from Southern Highway project (Colombo, Sri Lanka) is used for laboratory tests. The rate of secondary consolidation is discussed in detail, with laboratory tests to derive relevant soil parameters.**

Other major section involved in understanding the impact of over consolidation, to interpret the real world application of preloading for ground improvement. The laboratory test models considered are: stress- strain curve for loading-unloading-reloading sample and B'Jerrum Graphs model. Results are presented in diagram to quantify the reduced rate in consolidation for over consolidated soil samples. Further, correlation between consolation rate and Over Consolidation (OCR) are discussed in detail with aid of Mersi & Godlewski model.

Keywords—Secondary Consolidation; Buisman model; Preloading; B'JerrumGraphs; OCR;

I. INTRODUCTION

Secondary consolidation is a more complex progress occurs due to the effect of creep in soft soil. This creep action is more complex to model as the real reason for the soil particles' arrangement is unknown or not very obvious. Therefore, this is a research area has lot of scope to observe the properties behind this natural occurrence and the methodologies available to restrict the effect of them.

Terzaghi stated that, "consolidation is any process which involves decrease in water content of a saturated soil without replacement of water by air". Initially when a load is applied on the soil, the effective pressure increase will be balanced by the pressure increase in pore water. Due to the higher surcharge pressure, water tends to overcome its intermolecular attraction and escape from these voids. Thus with the dissipation of water, the volume reduces.

In the first ever classical theory on consolidation, Terzaghi quantified ted the one dimensional consolidation by following equation (1),

$$\frac{\partial u}{\partial t} = C_v \frac{\partial^2 u}{\partial z^2} \quad \text{...} \ (1)$$

Where coefficient of consolidation, $C_v = \frac{M}{\gamma_w}.k$

u – pore water pressure, t – time, z – depth, k – permeability of soil, M – compressibility of soil and γ_w - unit weight of water.

The model predicted consolidation to be a function of excess pore water pressure thus ultimate consolidation takes place with the dissipation of excess pore water. But later the observations show that soft clays undergo significant settlement in absence of excess pore water. Therefore the use of equation (1) is limited since it ignores the intrinsic time dependent creep effect of the soil.

This phenomenon known as secondary consolidation takes place due to the plastic movement among soil particles. Though there isn't any clear description, to gain more stable structure these soil particles are believed to be rearranging within themselves. Terzaghi (1941) and Taylor (1942) explained secondary consolidation as the readjustment of grains delayed by the gradual transfer of stress from film to grain bond. The basic assumption for this mechanism is that when a soil element is loaded, the total stress is shared by pressure in the free pore water, the viscous resistance within absorbed soil (film bond) and the bond between soil particles. During secondary consolidation, where the pore water is negligible, the total stress is shared by the film and grain bond. The pressure on the film gradually transferred to the grain body, and this transferring process is associated with very slow viscous flow. When the equilibrium state is reached, the applied load will be supported solely by grain bonds.

II. LITERATURE REVIEW

A. EOP & Secondary Consolidation Coefficient (C_α)

In 1936 Buisman identified secondary consolidation to occur in an approximate linear pattern, when he plotted change of strain against logarithmic time for an oedometer test.

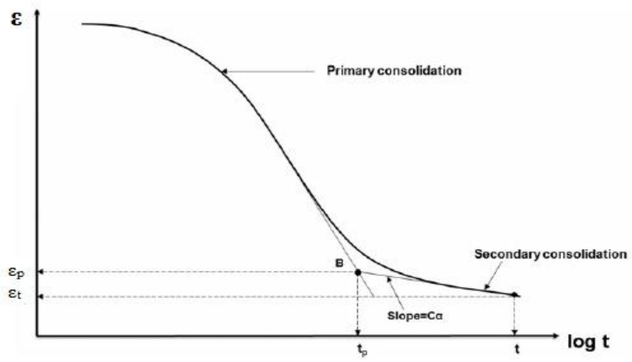

Fig 1 : Buisman's Oedometesr test model

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The end of primary consolidation (EOP) is taken as the point where gradient of both slope intersects as shown in Fig 1 (t_p). The gradient of trend under secondary consolidation defined as secondary consolidation coefficient C_α. Later in 1968, Walker and Raymond found that Cα appeared to be linearly dependent on C_c, the compression index of the soil. The $C\alpha/C_c$ factor explains and predicts the secondary consolidation behavior of geotechnical materials with and without surcharging (Mersi and Godlewski 1977, 1979). This concept is applied to laboratory tests and to determine the settlement of secondary consolidation (Mersi 1986). When $C\alpha/C_c$ is less, the secondary consolidation effect would be less.

B. B'Jerrum Graphs and OCR

For a long time, it is believed that creep and dissipation of pore water occur in two different phases which are namely discriminated as primary and secondary consolidation. But in 1957, Suklje described that creep is a continuous process that even occurs in the primary consolidation phase and presented a isotache model – the unique relationship between effective stress, void ratio and strain rate.

B'Jerrum presented a model on 1967, similar to Suklje's model assuming that primary consolidation and creep strains are not divided into separate processes. The model represents the pre-consolidation pressure or over consolidation ratio of virgin clays, resulting from geological ageing. The clay which is under same effective stress, for a longer time yields more settlement (i.e. less void ratio). This shows the time dependency of the secondary consolidation and its independence from effective stress. B'Jerrum uses various time lines to explain how reduced creep rates resulting from the increased duration of loading.

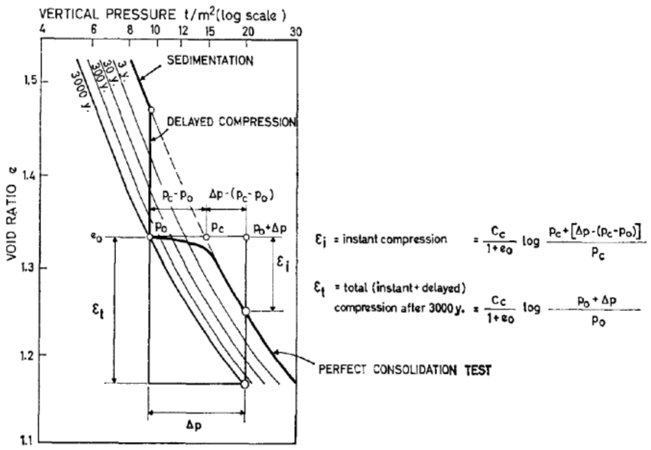

Fig 2 : B'Jerrum Graph (1967)

For the change of stress Δp, ε_t denotes the total strain comprises the effect of instant and delayed compression; ε_i denotes the strain only due to instant compression. This explains the effect of surcharge on soil and gives an idea of the age of load to achieve desired void ratio.

Also another important observation by Walker (1969) exposed that the Cα of a soil varies according to the ratio between the effective stress and effective stress at the end of pre-consolidation (σ_p). (Fig 3). Later Mersi and Godlewski(1977) found that Cα is not a function on effective stress, rather dependent on the over consolidated ratio that the soil experienced.

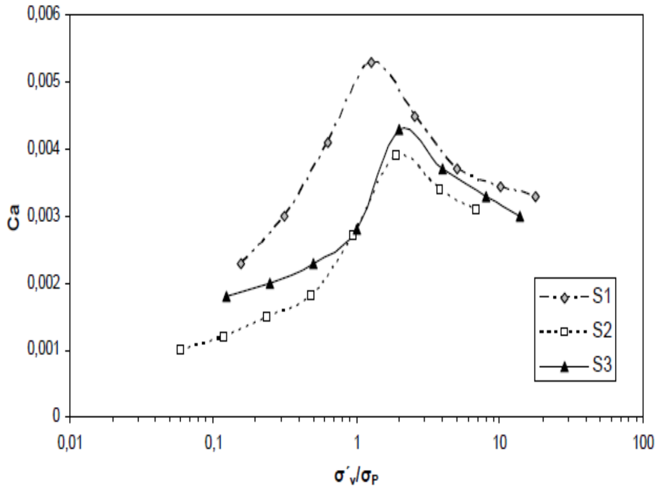

Fig 3 : C_α vs σ_v/σ_p (Walker 1969)

The dissipation of pore water during secondary consolidation leads to a more stable configuration of the structure. Such clay can support an additional load in excess of the effective overburden pressure without any significant volume change produced by slippage of the contact points. Thus, for additional loads smaller than a certain critical value the clay will behave similarly to an over consolidated clay and the instant settlements will be limited to an elastic compression. In the above figure 3, the Walker identified that Cα is maximum when effective stress is slightly higher than pre-consolidation stress. This observation is later proved in many other research works. But the significant observation in above trends is the decline in Cα on the side where pre-consolidation stress higher than the present effective stress, the phenomenon known as over consolidation.

Over consolidation rate (OCR) is defined as ratio between highest historical effective stress and present effective stress, on a sample. Mersi & Stark (1997) develop a model to illustrate how the post surcharge rate of secondary consolidation (Cα") with reference to its rate of secondary consolidation (Cα) changes in the pre - consolidated soil. Here the R_s' is given as $(\sigma'_{vs}/\sigma'_{vf} - 1)$ which is basically the residual OCR. Therefore it's proven that effect of secondary consolidation significantly reduces with historical loading.

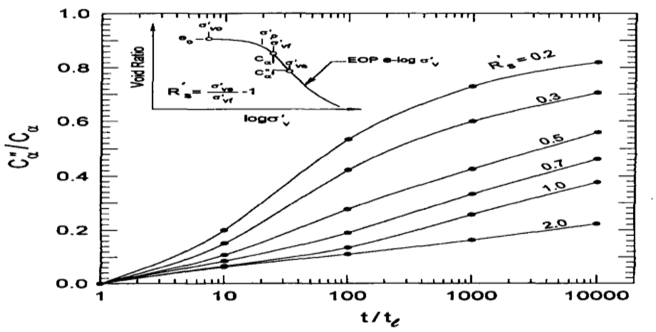

Fig 4 : Secondary settlement with surcharge, Mersi & Stark (1997)

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III. EXPERIMENTS AND OBSERVATIONS

Objective of laboratory experiments are to verify the classical models of Secondary consolidation and the effect of surcharge. The laboratory tests are involved in tracking down the strain variation for samples with different loading, using the Oedometer. The theories and tests for secondary consolidation, based on the assumption of one dimensional drain and settlement, which makes Oedometer the ideal simulation of ground conditions.

The peat samples are collected from the Southern Highway project, near Piliyandala (the highway connect Sothern district Matara, to Colombo). This sample is then cleaned, free of stones, organic matters and other large aggregates and then mixed well using beaker. As the sample was underground water for ages, the water content was higher for our practical purpose. Therefore the sample was left to dry for some degree until the optimum moisture content is obtained.

Fig 5 : Peat Sample as it's taken from the site & the Oedometer Testing in progress

A. *Experimental study to obtain B'Jerrum graph*

Four samples observed under different loading (5kN/m^2, 7.5kN/m^2, 10kN/m^2 & 15kN/m^2) , and the change in void ratio (settlement) with time is recorded. Readings are taken for 2 weeks.

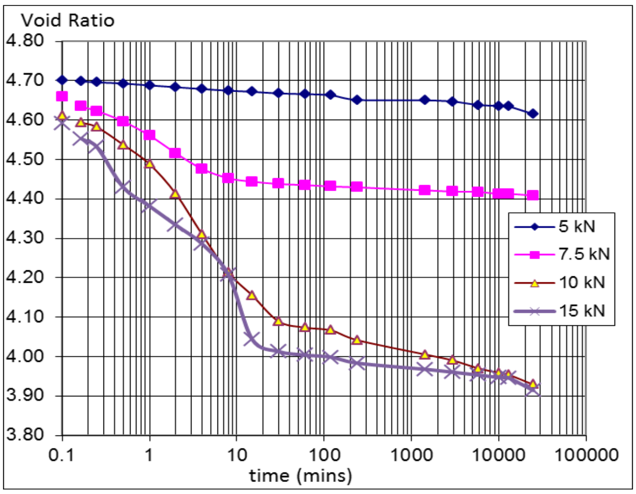

Fig 5 : Void ratio vs time trens for all samples in same axes

For 5kN/m^2 sample, the consolidation is hardly observable which leave higher amount of water content to be residual in the sample. This explains the importance of preloading with significant surcharge. Clear difference in instant and delayed settlement is apparent in higher loaded samples.

In order to derive B'Jerrum graphs , the void ratio at specific time is extracted from each individual graph (Fig 5) and plotted against the stress applied on respective sample.

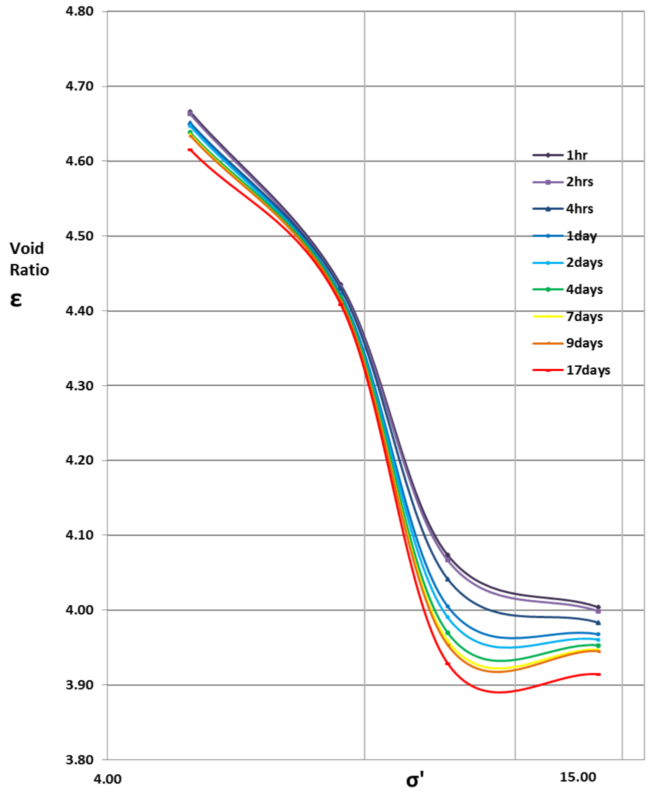

Fig 6 : B'Jerrum Graph for the peat samples

Since the time interval between readings was trivial compare to the time required for significant change in void ratio, the graphs appear to be congested. But still the difference becomes noticeable with the high values of stress applied.

B. *Determination of correlations between OCR and Cα/Cα'*

To examine the effect of secondary consolidation on over consolidated soil, 4 numbers of samples are implied with different equilibrium stress (σ_s) and OCR. The loading, unloading and re – loading trend for samples are as follow,

Sample A
0→10 → 20 → 40 → 80 → 88 → 96.8→106.8→ 96.8 → 88→ **80→ 88→ 96.8→106.8** (kN/m2)

Sample B
0→10 →20 →40 → 80 → 120 → 120→180→ 270→180 → 120 → **80 → 120 →180→270** (kN/m2)

Sample C
0→ 5 → 10 → 20 → 40 → 44 → 48.4 → 53.2→ 48.4 → 44 → **40→ 44→ 48.4 →53.2** (kN/m2)

Sample D
0→ 5 → 10 → 20 → 40 → 60 → 90 → 135 → 90 →60→ **40→ 60→ 90 →135** (kN/m2)

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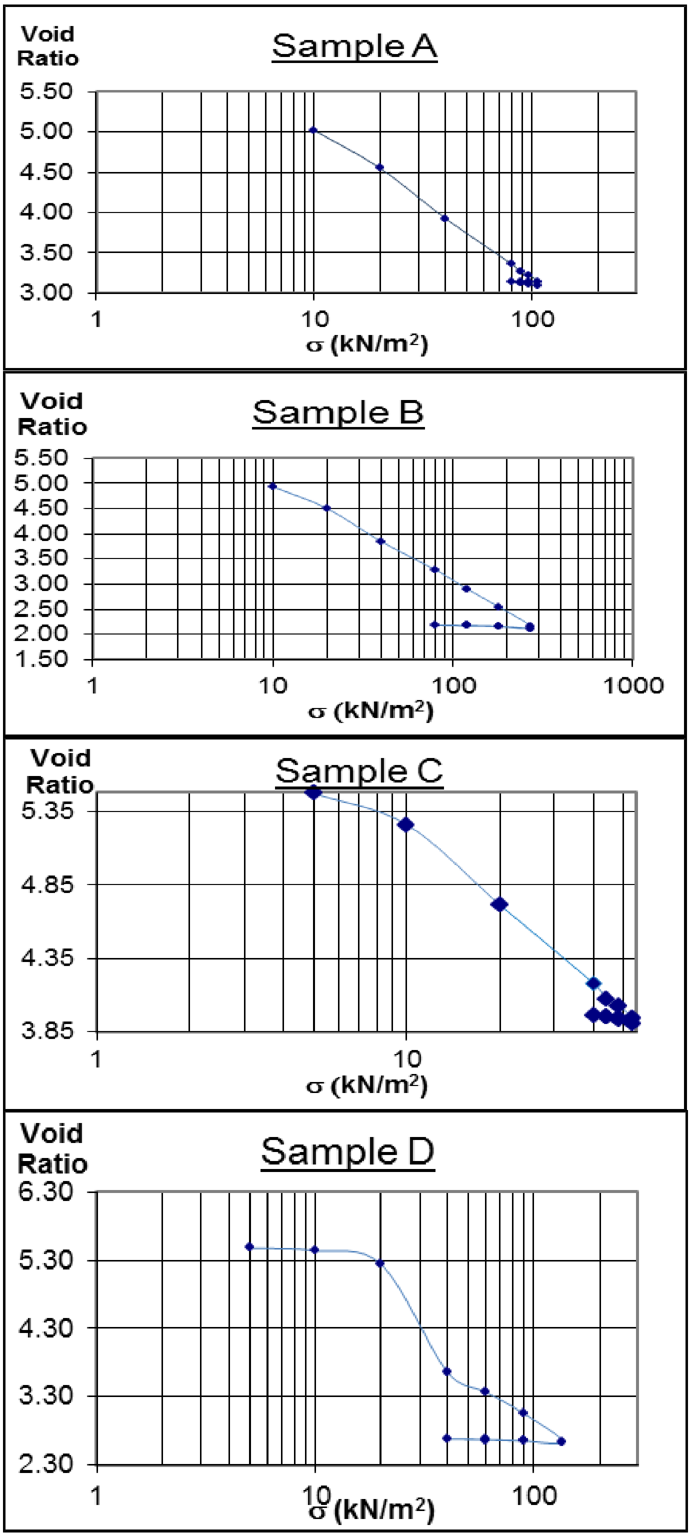

Fig 7 : Over consolidated peat samples' Stress vs Strain graphs

Each loading was kept for 3 days and individual Stress Vs Strain diagram was plotted to derive the C_α and Cα' values of the specific loading. Over consolidated peat showed a sharp decline in consolidation rate. These consolidation rates derived from each graph, for the loading phase (C_α) and the re-loading phase (C_α') are plotted to according OCR for each sample as shown in Fig 8.

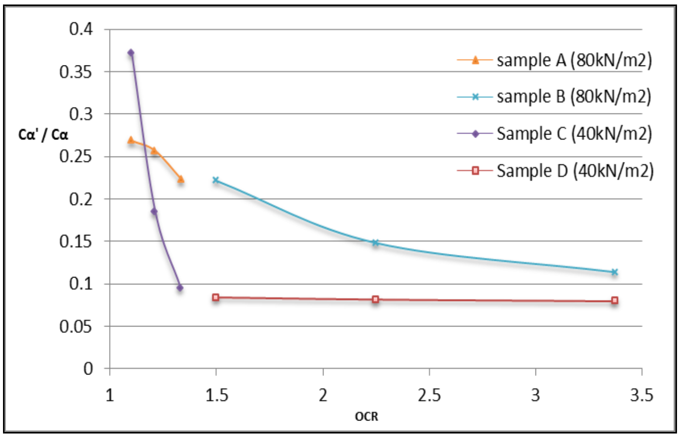

Fig 8 : C_α'/C_α vs OCR

The general observation of ratio C_α'/C_α reduces with the increase in OCR, satisfies the theory of Mersi & Stalk's model on soft clays under surcharge load. Further when considering the rate of decline in C_α'/C_α , the maximum rate is achieved in specific OCR for each equilibrium stress. For 80kN/m2 sample, the maximum rate is at 1.27 and for 40kN/m^2 is at 1.65. This phenomenon shows that C_α' depends on the effective stress at equilibrium. Finally this test explains the effect of historical load on Secondary consolidation.

IV. Conculsion

From the lab tests it's obvious that secondary consolidation is the major way of dissipating water in soft clays and peats where the water content is enormously larger compare to construction lands. When referring to the void ratio vs. time graph, primary consolidation in these soils occurs rapidly due to the higher compressibility of the soil and the pore water dissipates rapidly. During the lab tests, the peat samples achieved EOP within 10 to 30 minutes. Though the lab simulation only accounts for one dimensional compression, it compensates the loss of radial flow by providing more convenient drainage to flow. In contrary the water needs to travel through much longer drainage path.

After EOP (in e vs. log (time) diagram), the secondary consolidation appears to occur in a constant rate. This explains with the fact that C_α/C_c will remain specific unless the soil properties are disturbed. Further in detail it's found out that C_α/C_c changes with the loading arrangements of the samples. Referring to the literature review, Cα is also a time dependent factor, given that the considered time span is very long duration. However this wasn't been a critical issue in the aspects of geotechnical engineering, since however by means of ground improvement techniques the value of Cα will be minimized. And therefore, the change in Cα over the long span of time can be neglected.

Also another important characteristic which has to been taken under consideration is the surface drying effect of the soft clays and peat. In order to prevent this effect during experiment, the sample is kept saturated. When in field ground improvement procedure, it's vital to ensure that the surface is saturated to facilitate the load distribution along the soil profile.

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The results obtained from B'Jerrum graphs, shows that by preloading the instant settlement (as quoted by B"Jerrum) on soil can be reduced. Theoretically the graphs show that a constant load which is applied for a considerable time would affect the elastic compressibility of the soil. It explains that how the effects the instant settlement and time dependent settlement varies. It's clear that while increasing the stress the instant settlement will be higher and sudden. But when a constant stress applied for a considerable time, the instant settlement caused by the increase in stress would be lesser. This shows how the history of load on a soil affects its internal structure. Under the long term surcharge of load, soft clays overcome their weak bonding in between water particles and rearrange themselves with more soil particles' interaction. This ideology is easily explainable with the aid of obtained B'Jerrum model. But generally the practical application of this model is limited since B'Jerrum graphs doesn't account for factors affecting secondary consolidation. Therefore B'Jerrum model serve as the fundamental to understand the effect of surcharge loading.

From the the graphs plotted for soil undergoing series of loading, unloading and reloading, the significant significant reduction in the rate of compression on a preloaded soil is shown. The peat which experienced a higher load than present applied load seems to have a compact soil structure to minimize the creep effect. But from the results obtained from the graphs plotted for $C\alpha'/C\alpha$ vs. OCR shows that this reduction depends on the Over Consolidation Rate and the stress at which soil was in equilibrium (ie. after surcharge loading). These results show the great potential of this methodology has in practical aspect.

In a real life construction environment where soft clay/ peat is met , it's possible to improve the ground strength by deriving the ideal loading pattern by choosing the optimum OCR where the least void ratio can be achieved and the appropriate surcharge loading.

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