A Study on the Consolidation and Permeability Behaviour of Soils of State of Tamil Nadu, India

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Abstract. In order to study the consolidation behavior, clay soil samples from 20 various locations of Tamil Nadu, India were collected and subjected to one dimensional consolidation tests. Coefficient of consolidation $c_v$, coefficient of volume change $m_v$, and coefficient of permeability $k$ were plotted against consolidation pressure $\sigma$ for all the soils. The results showed that the variation of $c_v$ with pressure $\sigma$ is not constant for all the soils. It was observed that various soils have shown various trends. Hence, the trends obtained in the study were compared with the literature. From the study, it was found that the variations in the trends were due to mineralogical effects. The consolidation behavior of soil is found to be influenced by clay mineralogy. Similarly $k-\sigma$, $m_v-\sigma$ trends were also compared. The study shows that clay mineralogy has reasonable effects on the consolidation and permeability behavior of soil.

1. Introduction

Settlement occurs when a foundation is laid over the clay soil and leads to severe damages to the superstructure. Settlement is due to consolidation of soil beneath the foundation. Hence it is necessary to find the parameters causing the consolidation of soil. Consolidation is controlled by coefficient of consolidation $c_v$ [4] in which $c_v$ gives the rate of settlement of the soil. It is necessary to know the rate of settlement of clay for design purposes. The time required for a given amount of settlement is predicted using $c_v$. Since consolidation test is a time consuming process, many authors attempted to correlate $c_v$ with index properties like activity, liquidity index $I_l$ and plasticity index $I_p$ [5], shrinkage index $I_s$ [6], liquid limit $w_L$ [7,9], and Plasticity index $I_p$[8,9]. Coefficient of consolidation $c_v$ is a function of coefficient of permeability $k$ and coefficient of volume change $m_v$ [4] which is given as:

$$c_v = \frac{k}{m_v}$$

As the consolidation pressure increases, the soil shrinks in volume, because of expulsion of water from the soil pores. The rate of expulsion of water depends on the permeability of soil $k$. Hence, the consolidation and permeability of soil is studied using the parameters coefficient of consolidation $c_v$, coefficient of volume change $m_v$, and coefficient of permeability $k$ for the applied consolidation pressure $\sigma$. It is also observed that $c_v-\sigma$ trends for all soils were not same. $c_v$ of some soils were
increasing and some were decreasing. Analysing the variations in the $c_v$-$\sigma$ trends obtained in the laboratory for the clay minerals kaolinite, illite and montmorillonite and powdered quartz with water and CCl$_4$ as pore fluids, it was found that, the $c_v$ increased with consolidation pressure $\sigma$ for kaolinite and illite whereas it decreased for montmorillonite [11]. Variations in the $c_v$-$\sigma$ trend from various literatures have been tabulated in Table 1. According to Table 1, $c_v$ obtained in the present study is strongly influenced by clay mineralogy. The soils with increasing trends in the $c_v$-$\sigma$ plot may contain kaolinite and illite as dominant mineral and those with decreasing trend may have montmorillonite in greater amount.

Coefficient of volume change $m_v$ and coefficient of permeability $k$ decrease with increase in consolidation pressure $\sigma$ [11]. Higher range of values for $m_v$ was observed for montmorillonite ($1 \times 10^{-2}$ to $9 \times 10^{-5}$ m$^2$/kN), whereas, illite ($1.5 \times 10^{-3}$ to $1.5 \times 10^{-4}$ m$^2$/kN) and kaolinite ($2 \times 10^{-5}$ to $1 \times 10^{-4}$ m$^2$/kN) showed lower range of values. Kaolinite ($7 \times 10^{-7}$ cm/s to $1 \times 10^{-7}$ cm/s) showed higher range of values of $k$ whereas montmorillonite ($1 \times 10^{-8}$ to $1 \times 10^{-10}$ cm/s) showed lower range of values, illite ($7 \times 10^{-7}$ to $1 \times 10^{-7}$ cm/s) lies between the two. The present study has also shown decreasing trends for both $m_v$ and $k$ similar to [11]. Volume change behavior of soils is strongly influenced by mineral composition [17]. The influence of volume change behavior on $c_v$ increases with increase in consolidation pressure $\sigma$ [17].

| Soil Type          | $w_L$ | Dominant mineral | $c_v$-$\sigma$ trend | Reference |
|--------------------|-------|------------------|-----------------------|-----------|
| Kaolinite          | 49.0  | Kaolinite        | Increases             | [15]      |
| BC soil-1          | 73.5  | Montmorillonite  | Decreases             | [16]      |
| Illitic soil       | 73.4  | Illite           | Increases             |           |
| Montmorillonite    | 321   | Montmorillonite  | Decreases             | [11]      |
| Illite             | 131   | Illite           | Increases             |           |
| Kaolinite          | 53    | Kaolinite        | Increases             |           |
| Group M-I          | M-486 | Montmorillonite  | Decreases             | [13, 14]  |
| Group I-Q          | I-72  | Illite           | Increases             |           |
| Group K-I          | K-77  | Kaolinite        | Increases             |           |
| Bisaccia clay      | 110   | Smectite         | Decreases             | [17]      |
| Marino clay        | 50    | Kaolinite        | Increases             |           |

The coefficients of permeability $k$ of clays are controlled by both mechanical and physico-chemical factors [12]. The compressibility behavior of kaolinite, illite and powdered quartz is governed by mechanical factors and the compression behavior of montmorillonite is governed by physicochemical factors [11]. Mechanical factors denote size, shape, and the geometrical arrangement of the clay particles whereas physicochemical factors denotes i.e. diffused double layer [12]. Hence clay minerals like montmorillonite, kaolinite and illite plays a major role in consolidation behavior of clay. The individual effects of montmorillonite, kaolinite and illite on the consolidation behavior of soil were studied [11]. 40 different mixtures of montmorillonite, Kaolinite, Illite, and Quartz of various percentages were examined. The variation of compressibility and permeability of soil with the proportion of minerals and it was observed that compressibility of soil is heavily dependent on the mineral composition of soil specimen [13,14]. However, natural soil contains clay minerals in different proportions which are to be quantified in order to find the amount of dominant minerals in the soil.
Behavior of soil depends on the percentage of dominant mineral present in the soil. Each of the constituent clay mineral contributes to the macroscopic behavior. The proportions of the minerals in a soil sample are primarily responsible for the variations in the index properties, coefficient of consolidation, permeability, and the compression index [13].

2. Materials and experiments
Clay soil samples from 20 different locations of various districts of state of Tamil Nadu, India were collected in order to study the consolidation behavior of soil. Test pit method is used for collecting samples. Test pits are made at depths of 1 to 1.5 m and bulk, disturbed samples are collected from the pit. Then the soils are air dried, hand crushed and sieved in 425μ sieve and subjected to experimental tests in accordance with ASTM standards [1,2,3].

Soil samples are remolded at 1.1 times the liquid limit and compacted in three layers in the consolidation ring of 60 mm diameter and 20 mm height. The soil samples are subjected to one dimensional consolidation for the consolidation pressure range $\sigma$ of 25 kPa, 50 kPa, 100 kPa, 200 kPa, 400 kPa, 800 kPa, 1600 kPa.

3. Results and discussion
All the soils have been tested for index properties [1,2] and consolidation properties [3]. Liquid limit of the soils tested ranges from 25 to 61% and the clay fraction varies from 19 to 64%. Values of consolidation characteristics of $c_v$ and $m_v$ for all the soils are obtained from one dimensional consolidation tests. Coefficient of permeability $k$ is determined from equation 1.

When coefficient of consolidation $c_v$ is plotted against consolidation pressure $\sigma$, variations were observed in the trends of $c_v$-$\sigma$ plot. Table 2 lists $c_v$-$\sigma$ response and the dominant mineral in the soils of the present study predicted based on the findings in Table1. From Table 2, it can be seen that, liquid limit ranges from 25-30% for kaolinite, 29-40% for illite and 46-62% for montmorillonite dominated soils. Coefficient of volume $m_v$ and coefficient of permeability $k$ decreases with increase in consolidation pressure $\sigma$ for all the soils tested.

| Sample No. | W.L. | USCS classification | $c_v$-$\sigma$ response | Dominant mineral predicted based on literature review |
|------------|------|---------------------|------------------------|-----------------------------------------------------|
| S1         | 30   | CL                  | Increases              | Kaolinite                                           |
| S2         | 62   | CH                  | Decreases              | Montmorillonite                                    |
| S3         | 49   | CH                  | Decreases              | Montmorillonite                                    |
| S4         | 25   | ML                  | Increases              | Kaolinite                                           |
| S5         | 61   | CH                  | Decreases              | Montmorillonite                                    |
| S6         | 60   | CH                  | Decreases              | Montmorillonite                                    |
| S7         | 44   | CH                  | Decreases              | Montmorillonite                                    |
| S8         | 46   | CH                  | Decreases              | Montmorillonite                                    |
| S9         | 42   | CH                  | Decreases              | Montmorillonite                                    |
| S10        | 29   | CL                  | Increases              | Illite                                              |
| S11        | 37   | CL                  | Increases              | Illite                                              |
| S12        | 46   | CH                  | Decreases              | Montmorillonite                                    |
Increases Illite
S14 30  ML  Increases  Kaolinite
S15 32  CL  Increases  Illite
S16 40  CL  Increases  Illite
S17 32  CL  Increases  Kaolinite
S18 50  CH  Decreases  Montmorillonite
S19 58  CH  Decreases  Montmorillonite
S20 55  CH  Decreases  Montmorillonite

In order to study the variations clearly, three samples S4, S16 and S18 with predicted dominant mineral as kaolinite, illite and montmorillonite respectively are considered and analysed using cv-σ, mv-σ and k-σ plots. Figure 1 gives log of time versus compression curve for the consolidation pressure of 25 kPa for the considered soil samples S4, S16 and S18.

![Figure 1. Time – compression curve for the consolidation pressure of 25 kPa for the soil samples S4, S16, S18 where K, I, M indicates Kaolinite, illite, montmorillonite dominated soil.](image)

3.1. Factor affecting the variations in the cv-σ plot
Soils S4, S14, S17, S1, S15, S10, S16, S11, S13, S7 have shown increasing trends whereas soils S9, S8, S20, S19, S5, S12, S2, S3, S18, S6 have shown decreasing trends. Table 1 show that the variation in the cv-σ plot is due to the presence of dominant mineral in the soil. However soils will not contain only one mineral. But the soil exhibits the behavior of dominant mineral as shown in Table 1. The consolidation and swelling behavior of kaolinite and illite dominated soils were similar [13]. This is evident from figure 2 in which S4 and S16 has shown increasing trend and the dominant mineral is predicted as kaolinite and illite for S4 and S16 respectively. S18 with montmorillonite as dominant mineral has shown decreasing trend.
5.

Figure 2. Variation of $c_v$ with $\sigma$ for the soil samples S4, S16, S18 where K, I, M indicates kaolinite, illite, montmorillonite dominated soil.

3.2. Volume change behavior of soil samples tested
As the consolidation pressure increases, water diffuses away from the soil, thus soil gradually takes up the pressure and shrinks in volume. Volume change is influenced by stress level [17]. The volume change is governed by two mechanisms. For kaolinite clay shearing resistance at inter particle level predominate and for montmorillonite clay, the volume change is caused by the diffuse double layer repulsive forces [19]. The shear resistance of kaolinite is a function of clay fabric and surface friction [20]. Figure 3 shows the response of $m_v$ with $\sigma$ for the soil samples S4, S16 and S18 for which dominant mineral is predicted as kaolinite, illite, and montmorillonite respectively. The plot obtained in the present study is similar to that obtained for kaolinite, illite and montmorillonite in [11]. Thus the predicted dominant mineral matches.

Figure 3. Variation of $m_v$ with $\sigma$ for the soil samples S4, S16, S18 where K, I, M indicates kaolinite, illite, montmorillonite dominated soil

3.3. Permeability behavior of soil samples tested
$k$-$\sigma$ plot is obtained for soil samples S4, S16 and S18 as shown in figure 4. Coefficient of permeability $k$ showed higher range of values for kaolinite, lower range of values for montmorillonite and illite lies
between the two [11]. From figure 4, it is seen that higher range of values of k were observed for S4 and S16 with kaolinite and illite as dominant mineral and lower range of values were observed for S18 with montmorillonite as dominant mineral. The trend obtained in the present study is similar to [11]. Permeability of soil k depends on mechanical and physico chemical i.e., kaolinite and illite are greatly influenced by mechanical factors whereas montmorillonite is influenced by physico chemical factors [18]. Thus, the behavior of kaolinite and illite are governed by short-range particle interactions due to grain size and shape whereas the behavior of montmorillonite is governed by long-range particle interactions due to diffused double layer [11].

Kaolinite and illite dominated soils exhibited similar consolidation behavior. This is evident from Fig. 4 in which S4 and S16 show increasing trend and the dominant mineral is predicted as kaolinite and illite for S4 and S16 respectively. The trends of S4 and S16 for all c_v-σ, m_v-σ, k-σ plots lies closer whereas more gap exists for S18. This indicates that kaolinite and illite dominated soils exhibit similar behavior (short range particle interaction), but montmorillonite exhibits physico chemical behavior (long range particle interaction).

![Figure 4. Variation of k with σ for the soil samples S4, S16, S18 where K, I, M indicates kaolinite, illite, montmorillonite dominated soil](image)

### 3.4. Relationship between c_v and Index properties

#### Table 3. Correlations for c_v using index properties from various literatures

| S.No. | Equation | R²  | Source |
|-------|----------|-----|--------|
| 1.    | $c_v = \frac{3}{100(I_r)^{1/5}}$ (m²/s) | 0.94 | [16]   |
| 2.    | $c_v = -4 \times 10^{-9} w_c + 4 \times 10^{-7}$ (m²/s) | 0.8298 | [10]   |
| 3.    | $c_v = 0.6155 - 0.0183 I_p$ (m²/yr) | 0.994 | [8]    |
In order to calculate $c_v$, correlations between $c_v$ and index properties given by many literature are listed in Table 3. Index properties $w_L$, $w_p$, $w_S$, $I_P$ and $I_S$ are plotted against $c_v$ for all consolidation pressure range $\sigma$ of 25 kPa, 50 kPa, 100 kPa, 200 kPa, 400 kPa, 800 kPa, 1600 kPa as shown in figure 5 and figure 6. For the soil samples tested, shrinkage limit correlates better with $c_v$ than any other parameter, and with $R^2=0.824$ for which correlation is as follows:

$$c_v = 3E^{-21} f_s^{10.86}$$

(2)

4. Conclusion
- The present study shows that shrinkage limit has a better correlation with coefficient of consolidation than the liquid limit, plastic limit and shrinkage index.
- Variation in $c_v$-$\sigma$, $m_c$-$\sigma$, $k$-$\sigma$ plots were observed for all the soils and it was found that the dominant clay mineral present in the soil sample is responsible for the variation.
The dominant clay mineral is predicted for the soil samples of the present study on the basis of literature review (Table 1).

The trends obtained for $c_v$-$\sigma$, $m_v$-$\sigma$, $k$-$\sigma$ with kaolinite, illite and montmorillonite dominated soils matches well with [11].

The response of $c_v$, $m_v$, $k$ for kaolinite and illite dominated soils were similar as stated by [13].

Works were carried out on pure minerals and mineral mixtures (controlled condition) [11,14]. But the present study involves testing of natural soil samples.

The proportion of each mineral present in the soil varies for all the soil. Each mineral amount has their individual effect on the consolidation behavior of soil.

Hence quantification of minerals is necessary in order to study effect of individual mineral on the consolidation behavior of the soil.

Here in this study only three clay minerals were considered. But the presence of other clay minerals wills also have their significant effect on the behavior of soil.

In summary, it is concluded that when combinations of mineral exists in sampled soil, especially containing clay, consolidation behavior and permeability behavior at various consolidation pressure, can be indicative of the dominant mineral present.

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