A Review on Correlations for Consolidation Characteristics of Various Soils

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Abstract. Settlement is the major problem that arises after the construction of a structure on a soil mass. Consolidation characteristics of soil such as coefficient of consolidation \(c_v\), compression index \(c_c\), recompression index \(c_r\), preconsolidation pressure \(\sigma'_p\) play a major role in the settlement behavior of fine grained soil mass. \(c_v\) represents the rate of consolidation of soil mass. \(c_c\) and \(c_r\) are essential in calculating settlement of normally and over consolidated clays respectively. \(\sigma'_p\) is determined to find whether the clay is under, normally or over consolidated. These consolidation properties are obtained from graphical constructions after conducting several one dimensional consolidation-oedometer tests. Since this is time consuming, many correlations have been derived between consolidation properties and index properties of soil. Different researchers have used various soil parameters such as liquid limit (\(w_L\)), plastic limit (\(w_p\)), natural moisture content (\(w_n\)), initial insitu void ratio (\(e_0\)), dry unit weight (\(\gamma_d\)), plasticity index (\(I_p\)), void ratio at liquid limit (\(e_L\)) etc., as correlative parameters for deriving the correlations. Hence, it is desirable to predict the value of \(c_v\), \(c_c\), \(c_r\) and \(\sigma'_p\) from the known correlations rather than conducting several tests, to ease the procedures.

1. Introduction
The determination of settlement of soil mass is most important during the construction of structure on a soil. Settlement is due to compressibility of soil mass. The consolidation characteristics of soil like compression index \(c_c\) and coefficient of consolidation \(c_v\) play a vital role in predicting the compressibility of soil mass. Settlement is estimated from compression index \(c_c\) which is obtained from void ratio \(e\) versus vertical effective stress \(\sigma'\) in the semi-logarithmic plane. Coefficient of consolidation \(c_v\) is used to predict the time required for a given amount of compression to take place i.e., rate of settlement. Casagrande’s logarithm of time fitting \([2]\) and the Taylor’s square root of time fitting methods \([4]\) are widely accepted as standard methods for determination of \(c_v\). Other consolidation characteristics of soil such as recompression index \(c_r\) and preconsolidation pressure \(\sigma'_p\) are also important in predicting the compressibility behavior of the soil mass. \(c_c\) and \(c_v\) which are slopes of virgin curve and recompression curve respectively (\(e\) versus log \(\sigma'\) plot) for calculating the settlement of normally and over consolidated clays respectively. In order to find whether the clay is normally or over
Consolidated, it is necessary to determine $\sigma'_p$. Casagrande’s [3] construction is the most popular method for determining $\sigma'_p$. These consolidation characteristics are obtained from data of several one-dimensional consolidation tests according to ASTM Standard [1] using oedometer apparatus for varying loading increments. The collected data are plotted as graphical construction, from which the consolidation characteristics are determined. The soil specimen in the oedometer can also be tested for various conditions like incremental loading [4,5], constant rate of strain (CRS) [6,7], controlled Gradient tests (CG Test) [8,9] and continuous loading (CL test) [10]. Thus the laboratory oedometer test takes more time to determine these consolidation characteristics. Hence equations have been developed for predicting consolidation properties, which can be used without conducting oedometer tests, thus saving considerable time. The paper reviews the correlation for $c_v$, $c_c$, $c_t$ and $\sigma'_p$ using soil properties like activity (ACT), liquidity index $I_L$, plasticity index $I_p$, shrinkage index $I_s$, liquid limit $w_L$, plastic limit $w_P$, initial void ratio $e_0$, natural moisture content ($w_n$), initial in situ void ratio ($e_o$), dry unit weight ($\gamma_d$), plasticity index ($I_p$), and void ratio at liquid limit ($e_L$) as correlative parameters.

2. Prediction of coefficient of consolidation $c_v$ from soil properties

An equation for one-dimensional consolidation of cohesive soil layer under sustained loads considering the length of the drainage path given by [5] is expressed as:

$$T = \frac{c_v t}{H^2}$$  \hspace{1cm} (1)

Where $t$ is the time for consolidation, $T$ is the time factor and $H$ is the length of the longest drainage path or thickness of the consolidating layer. The drainage path for double drainage is equal to $H/2$ and for single drainage, it is equal to $H$. The dimensionless factor $T$ is derived from degree of consolidation $U$ (%), for $U<60\%$, $T=(\pi/4) \left(\frac{U}{100}\right)^2$, for $U>60\%$, $T=1.781-0.933 \log (100-U)$ [2,12]. $c_v$ is calculated using Casagrande’s logarithm of time fitting method [3], Taylor’s square root of time fitting method [12] Inflection point method [13], Analytical method [14], Velocity method [15,16], Rectangular Hyperbola Fitting Method [17] which consumes more time by conducting oedometer test for more than a week. In recent days, index properties of soil are used in correlating many engineering properties of soil.

| S.No. | Equation | Applicability | source |
|-------|----------|---------------|--------|
| 1.    | $c_v = \frac{9.09 \times 10^{-7} \{1.192 + ACT^{-1}\}^{0.998} (4.135 I_L + 1)^{1.29} \{2.03 I_L + 1.192 + ACT^{-1}\}^{0.998}}{I_L (2.03 I_L + 1.192 + ACT^{-1})^{0.998}} \left(\text{m}^2/\text{s}\right)$ | Normally consolidated clays | [18] |
| 2.    | $c_v = \frac{1 + e_0 \left(1.23 - 0.276 \log \sigma'_p\right)}{e_L} \times \frac{1}{\sigma'^{0.333}} \times 10^{-3} \left(\text{cm}^2/\text{s}\right)$ | Normally consolidated clays with $w_L$ 50-106% and $w_P$ 27-47% | [21] |
From Table 1, it can be seen that index properties like liquid limit ($w_L$), liquidity index ($I_L$), plasticity index ($I_p$), shrinkage index ($I_s$), activity ($ACT$), void ratio at liquid limit ($e_L$) are used as a single parameter or multiple correlative parameters for predicting coefficient of consolidation $c_v$. Experiments were conducted on normally consolidated clay and it was observed that $c_v$ decreases with decrease in water content and it is inversely proportional to $I_p$[18]. $c_v$ has a better correlation with shrinkage index $I_s$ than plasticity index $I_p$ or liquid limit $w_L$ and it was reported that ample scope exists for undisturbed and over consolidated soils [19]. Liquid limit $w_L$ gives better correlation with $c_v$ than shrinkage index $I_s$ and plasticity index $I_p$ [20].

3. Prediction of compression index $c_c$ from soil properties

Compression index $c_c$ is a main parameter in predicting time dependent consolidation settlement ($S_c$) as given in the equation 2. Hence it is necessary to find $c_c$ in order to calculate $S_c$. For a layer of normally consolidated clay of thickness $H$, initial void ratio $e_0$, compression index $c_c$, and effective overburden pressure $\sigma'_0$, the total settlement $s_c$ under an applied load increment $\Delta\sigma'$ can be expressed as:

$$s_c = c_c H \log \frac{\sigma'_0 + \Delta\sigma'}{\sigma'_0}$$

Eq. (2)

$c_c$ is the slope of the compression curve $e - \log \sigma'$ plot and the expression is given as $c_c = \Delta e/\log (\sigma'_2/\sigma'_1)$, where $\Delta e$ is the change in void ratio for the corresponding effective vertical stress. The conventional one dimensional consolidation by oedometer test is time consuming in determination of $c_c$. In order to reduce the effort, many correlations exist between $c_c$ and soil index properties like $w_L$, $I_p$, $w_n$, $e_o$, $\gamma_d$ as a single or multiple correlative parameter, as tabulated in Table 2, for different regions and applicability. Hence these empirical equations can be used directly for predicting $c_c$ based on its applicability without undergoing conventional oedometer tests.
Table 2. Correlations for $c_e$

| S.No. | Equation                                                                 | Applicability               | source |
|-------|---------------------------------------------------------------------------|------------------------------|--------|
| 1.    | $c_e = 0.007(w_L - 10)$                                                   | Remoulded clays             | [11]   |
| 2.    | $c_e = 0.54(e_a - 0.35)$  \[c_e = 1.15(e - e_o)\]                        | Normally consolidated clays | [34]   |
| 3.    | $c_e = 0.001(w_L - 12)$                                                   | Osaka alluvial clays        | [33]   |
| 4.    | $c_e = 0.009(w_L - 10)$                                                   | Normally consolidated clays | [25]   |
| 5.    | $c_e = 0.0083(w_L - 9)$                                                   | Various clays               | [35]   |
| 6.    | $c_e = 0.006(w_L - 9)$  \[c_e = 0.4(e_o - 0.25)\]  \[c_e = 0.01(w_n - 5)\] | All clays with $w_L<100\%$ | [26]   |
| 7.    | $c_e = 1.35f_r$                                                          | Remoulded clays of Gulf of Mexico and North Sea | [36] |
| 8.    | $c_e = 0.0092(w_L - 13)$  \[c_e = 0.0072(f_r + 26)\]                     | All Clays                   | [37]   |
| 9.    | $c_e = 0.011w_n$                                                         | Chicago clays               | [27]   |
| 10.   | $c_e = 0.2343e_L$                                                        | Remoulded normally consolidated clays | [28] |
| 11.   | $c_e = 0.329\left[0.027(w - w_p) + 0.0133\left(f_r + 1.192 + ACT^{-1}\right)\right]$ | Normally consolidated clays | [18]   |
| 14.   | $c_e = 0.256e_L - 0.04$                                                  | Reconstituted clay Soil lying above A-Line | [29] |
| 15.   | $c_e = 0.009(w_L - 8)$                                                   | Osaka Bay Clay              | [38]   |
| 16.   | $c_e = 0.008(w_L - 12)$  \[c_e = 0.007(f_r + 18)\]                      | All Clays                   | [30]   |
Skempton[11] was the first to give empirical correlation for $c_c$ of remoulded soils with liquid limit $w_L$. Colloidal clays are more compressible and possess higher void-ratios under a given pressure than the sandy clays and silts[11]. A modified equation for normally consolidated clays was given by [25]. $e_0$ and $w_o$ were utilised to obtain best correlae model for the determination of both $c_c$ and $c_r$ than $w_L$ [26]. Ridge regression holds well in dealing with multicollinearity in regression models [27]. $c_c$ decreases with decrease in the water content and it is directly proportional to the plasticity index [18]. The normally consolidated $e$ versus log $\sigma'$ curves of different fine grained soils were normalized by their respective $e_L$ values where $e_L=w_L/(G_s+e_0)$ and equations were developed for the stress and time dependent nature of preconsolidation pressure [28].

A normalizing parameter called void index, $I_v$ was introduced in order to differentiate the properties of reconstituted clay (i.e., intrinsic compression characteristics of clay) from the natural clay soil [29]. It

|   |   |   |   |
|---|---|---|---|
| 17. | $c_c = 0.0012(w_L + 16.4)$ | $c_c = 0.013(w_o - 3.85)$ | South coast of Korea |
|   | $c_c = 0.54(e_0 - 0.37)$ | $c_c = -1.6\gamma_d - 2.4$ |   |
|   | $c_c = -0.0003w_o + 0.538e_0 + 0.002w_L - 0.3$ | [39] |   |
| 18 | $c_c = 0.01w_o$ | Undisturbed fibrous peat | [31] |
| 19 | $c_c = 0.0061(w_L - 0.0024)$ | $c_c = 0.0082I_p + 0.0915$ | Alluvial deposits, Surat, India |
|   | $c_c = 0.0091w_o + 0.0522$ | [40] |   |
| 20 | $c_c = 0.0055(w_L - 1.8364)$ | $c_c = 0.0055(I_p + 21.2364)$ | Highly plastic clays of Kuttanad, Kerala, India |
|   | $c_c = 0.0086(I_p + 24.2674)$ | $c_c = 0.2875(e_0 - 0.5082)$ | [32] |
| 21 | $c_c = 0.013(w_o - 0.115)$ | $c_c = 0.49(e_0 - 0.11)$ | Republic of Korea |
|   | $c_c = 0.014(w_L - 0.168)$ | [41] |   |
|   | $c_c = 0.009w_o + 0.005w_L$ | $c_c = 0.013w_o + 0.0w_L + 0.168$ |   |
| 22 | $c_c = 0.0118(w_L - 20.7)$ | $c_c = 0.014(w_o - 22.7)$ | Irish soft soils |
| 23 | $c_c = 0.0062w_L + 0.0165$ | Remoulded soil with $w_L$ 29% to 46% and $I_p$ 8 to 18 | [24] |

Irish soft soils

Remoulded soil with $w_L$ 29% to 46% and $I_p$ 8 to 18
has been demonstrated that intrinsic compression line (ICL) and sedimentation compression line (SCL) is a valuable reference line in studying the compression characteristics of natural, normally and over consolidated clays. However ICL can be obtained by plotting \( I_v^* \) versus \( \log \sigma' \) for every increase in \( \sigma' \). Similarly SCL can be obtained by plotting \( I_{v0}^* \) and \( \log \sigma' \). \( I_v^* \) and \( I_{v0}^* \) can be calculated from the equation 3 and equation 4.

\[
I_v^* = \frac{e^* - e_{100}^*}{c^*_c} \quad \text{(3)}
\]

\[
I_{v0}^* = \frac{e_{00}^* - e_{100}^*}{c^*_c} \quad \text{(4)}
\]

Where \( I_v^* \) = intrinsic void index
\( e^* \) = intrinsic void ratio at various preconsolidation pressure
\( e_{100}^* \) = intrinsic void ratio at 100 kPa preconsolidation pressure
\( c^*_c \) = intrinsic compression index =\( e_{100}^* - e_{100}^* \)

The normally consolidated soil lying between ICL and SCL, for a given value of \( I_{v0}^* \), the effective overburden pressure taken by the natural clay is almost five times that for reconstituted clay. For overconsolidated clays, ICL and SCL are helpful in assessing the degree of overconsolidation [29].

The soil with a lower shrinkage index compresses less than a soil with a higher shrinkage index, even though their liquid limits are about the same [30]. The fibrous peat possesses very high water content of 500% to 2000% and very high permeability of 1000 times the initial permeability of soft clays. Fibrous peat deposits compresses extremely with an increase in effective vertical pressure and it exhibits highest value of secondary compression and lowest duration for primary consolidation [31]. Shrinkage index \( I_s \) is found to be the most suitable generalization parameter to characterize the compressibility behavior of highly plastic soil of Kuttanad region in the State of Kerala, India [32].

4. Determination of recompression index \( c_r \)

Over consolidated soils are probably encountered more often than normally consolidated soils. Moreover, if the soil is overconsolidated, it is necessary to determine settlement due to overconsolidation. The soil is overconsolidated, when the preconsolidation pressure \( \sigma'_p \) is greater than the existing vertical overburden pressure \( \sigma'_0 \). So, the first thing is to check whether the soil is preconsolidated. However, \( \sigma'_p \) is determined by plotting \( e \) versus \( \log \sigma' \) through graphical construction [3]. Equation 5 and equation 6 gives recompression index \( c_r \) for overconsolidated clays of thickness \( H \) to compute the level of settlement.

When \( \sigma'_0 + \Delta \sigma' \leq \sigma'_p \),

\[
s_c = \frac{c_r}{1 + e_0} H \log \frac{\sigma'_0 + \Delta \sigma'}{\sigma'_0} \quad \text{(5)}
\]

When \( \sigma'_0 + \Delta \sigma' > \sigma'_p \),

\[
s_c = \frac{c_r}{1 + e_0} H \log \frac{\sigma'_p}{\sigma'_0} + \frac{c_r}{1 + e_0} H \log \left[ \frac{\sigma'_0 + \Delta \sigma'}{\sigma'_p} \right] \quad \text{(6)}
\]
Recompression index \( c_r \) is the slope of the recompression curve obtained when void ratio \( e \) is plotted against effective vertical stress \( \sigma' \) in a semi logarithmic plot. Since the determination of \( c_r \) from oedometer tests is relatively time-consuming and is usually determined for a single unloading, empirical equations based on index properties can be useful for settlement estimation. Correlations have been proposed to relate the \( c_r \) of clay deposits to other soil parameters as given in Table 3. \( c_c \) and \( c_r \) are not only affected by over consolidation ratio, but also by other physical properties of soil like initial void ratio \( e_0 \). Increase in \( e_0 \) decreases \( c_c \) and \( c_r \) and increase in OCR, increases \( c_c \) and \( c_r \) [43]. Artificial neural networks (ANN) perform better in developing regression equations than the regression analysis [44].

### Table 3. Correlations for determining \( c_r \)

| S.No. | Equation | Applicability | References |
|-------|----------|---------------|------------|
| 1.    | \( c_r = 0.0463e_L \) | overconsolidated saturated fine grained soils | [28] |
| 2.    | \( c_r = 0.14(e_0 + 0.007) \)  
\( c_r = 0.01(w_m + 7) \)  
\( c_r = 0.002(w_L + 9) \) | All clays with \( w_L <100\% \) | [26] |
| 3.    | \( c_r = 0.00084(I_p - 4.6) \) | remolded young natural clays | [45] |
| 4.    | \( c_r = -0.025 + 0.002w_m \)  
\( c_r = -0.024 + 0.0732e_0 \)  
\( c_r = 0.0048 + 0.001I_p \)  
\( c_r = -0.0214 + 0.0013w_L \) | Clay deposits | [46] |
| 5.    | \( c_r = 0.041 - 0.0268e_0 \)  
\( c_r = 0.0131 + 0.0254c_c \)  
\( c_r = 0.02 + 0.00052OCR \) | Turkish clays | [43] |
| 6.    | \( c_r = 0.0007w_L + 0.0062 \)  
\( c_r = 0.1257\gamma_d^{-2.8826} \) | Mazandaran Province of Iran | [44] |

### 5. Correlation between preconsolidation pressure \( \sigma'_p \) and soil properties

In order to find whether the soil is preconsolidated, it is necessary to determine preconsolidation pressure \( \sigma'_p \). Several procedures have been proposed to determine \( \sigma'_p \). Casagrande’s method [3], which is graphical construction method was widely used for determination of \( \sigma'_p \). Interpretation of preconsolidation pressure from incremental loading test is more difficult, when the incremental ratio is high. Controlled strain test is the fastest method of determination of \( \sigma'_p \) [16]. \( \sigma'_p \) determined using ANN model gives more accurate result than graphical method and void ratio is the effective parameter on preconsolidation pressure [47]. Correlations for \( \sigma'_p \) for different applicability are given in the Table 4.
Table 4. Correlations for determining $\sigma'_p$

| S.No | Equation | Applicability | References |
|------|----------|---------------|------------|
| 1.   | $\frac{e}{e_L} = 1.122 - 0.188 \log \sigma'_p - 0.0463 \log \sigma' \quad (\text{kN/m}^2)$ | overconsolidated saturated fine grained soils | [28] |
| 2.   | $\sigma'_p = 137.924 - 0.179\sigma' - 30.48 \left(\frac{e}{e_L}\right) \quad (\text{kN/m}^2)$ | alluvial deposits of south Gujarat region | [40] |

6. Conclusions
- It can be concluded that, the existing empirical correlations for the consolidation characteristics of soil, coefficient of consolidation $c_v$, compression index $c_c$, recompression index $c_r$ and preconsolidation pressure $\sigma'_p$ with soil parameters, as per the conditions of applicability and the methods used for deriving the correlations are reviewed extensively. The correlations are derived in terms of single or multiple soil parameters.
- Hence, by selecting the suitable equations, one can predict the values of $c_v$, $c_c$, $c_r$ and $\sigma'_p$ without conducting conventional oedometer tests.

Acknowledgement
The authors acknowledge with thanks, for the facilities offered, by the Department of Civil Engineering, National Institute of Technology, Tiruchirappalli, India. Also, grateful to the Ministry of Education (MoE), India, for providing scholarship, to carry out the research work.

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