International Journal of GEOMATE, Nov., 2017, Vol.13, Issue 39, pp.54-60
Geotec., Const. Mat. & Env., ISSN:2186-2990, Japan, DOI: https://doi.org/10.21660/2017.39.98271

DETERMINATION OF THE COMPRESSION INDEX OF RECONSTITUTED CLAYS USING INTRINSIC CONCEPT AND NORMALIZED VOID RATIO

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*Corresponding Author, Received: 8 May 2017, Revised: 23 May 2017, Accepted: 22 June 2017

ABSTRACT: Measurement of the compression indexes of clayey soils, particularly reconstituted clays with a high initial water content, is generally time-consuming and costly. A mitigation of these constraints could include a correlation between the compression indexes and the consistency limits of the clay soil that can be measured reliably. In this paper, the time-tested concepts of intrinsic framework and normalisation methods were used to derive a correlation between the compression indexes of reconstituted clays and the soil void ratios at consistency limits. The proposed method is based on the assumption that a unique relationship exists between consolidation pressures and consistency limits. Furthermore, the equation was simplified to estimate the compression index as a function of consistency indexes. Then, the equation was validated via comparison with a wide range of results reported in the literature regarding various types of clay. Results of this comparison suggest that there is an exclusive relationship between compression index and consistency limits for reconstituted clays.

Keywords: Compression index, reconstituted clay, liquid limit, plastic limit, clay

1. INTRODUCTION

The compression characteristic of soils, is a critical parameter in geotechnical engineering for the prediction of the settlement of structures, in particular if the foundation material is a clayey soil [1-3]. The rate of consolidation of a clayey layer can be identified by its compressibility, which is often expressed in terms of void ratio and effective vertical stress [4]. The slope of the linear portion of a compression curve, which is usually referred to as 'Virgin Compression Line' (VCL), is often used to represent the compressibility behaviour of a soil (Fig. 1) [4].

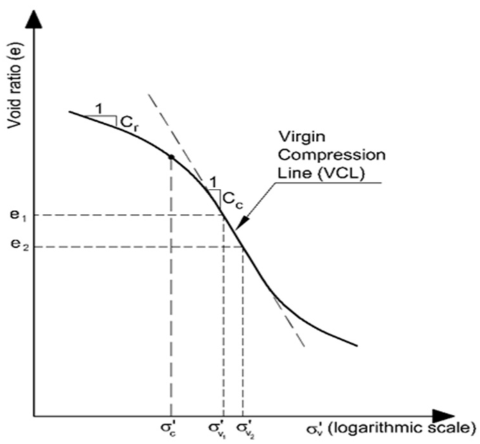


Fig. 1 Schematic plot of a compression curve in e-log σ'_v space (Redrawn from [4]).

The total settlement (ΔH) of a structure constructed on a clay layer can be estimated from the following relation [4]:

$$\Delta H = \frac{\Delta e \, H}{1 + e_0} \tag{1}$$

where H is the thickness of the clay layer, and e_0 is the void ratio at an initial effective stress of σ'_0. The decrease in void ratio (Δe) can be determined from the following equations, depending on the degree of preconsolidation of the clay layer [4].

For a normally consolidated clay:

$$\Delta e = C_c \, \log \frac{\sigma'_0 + \Delta\sigma}{\sigma'_0} \tag{2}$$

For an over-consolidated clay:

$$if \; \sigma'_0 + \Delta\sigma < \sigma'_c \,, \;\; \Delta e = C_r \, \log \frac{\sigma'_0 + \Delta\sigma}{\sigma'_0} \tag{3}$$

$$if \; \sigma'_0 < \sigma'_c < \sigma'_0 + \Delta\sigma \,, \tag{4}$$

$$\Delta e = C_r \, \log \frac{\sigma'_c}{\sigma'_0} + C_c \, \log \frac{\sigma'_0 + \Delta\sigma}{\sigma'_c}$$

where H is the thickness of the clay layer, e_0 is the void ratio at an initial effective vertical stress of σ'_0, $\Delta\sigma$ is the increment of stress applied to the clay layer, σ'_c is the preconsolidation stress of the clay layer, C_c is the virgin compression slope (compression index), and C_r is the recompression slope (recompression index). For a normally consolidated clay, the only parameter needed to compute Δe is C_c, which is the slope of the virgin compression line (i.e. the straight part of the compression curve) [2,4]. However, for an over-consolidated soil, there are two more parameters required to compute total settlement, namely, recompression index (C_r), and preconsolidation stress (σ_c').

Compressibility can be conventionally determined by laboratory or field tests [1-4]. However, such tests are cumbersome and expensive. They are particularly difficult for reconstituted samples such as marine clays that have been prepared at a water content greater than their liquid limit [5,6]. Therefore, it may be useful to estimate the compression index by simply measuring soil classification parameters such as liquid limit, plastic limit, natural water content, in situ void ratio, or porosity [7]. These parameters can also be measured reasonably accurately in most traditional geotechnical laboratories without the requirement for sophisticated testing. In the past six to seven decades, many researchers have proposed empirical relationships for a broad range of soil types and sample conditions to predict soil compressibility using the previously-mentioned geotechnical parameters [1-3, 7-20]. To name a few, a summary of some of these relationships is provided in Table 1.

Table 1 Some equations used to estimate the compression index of clays

Equations	Reference
$C_c = 0.007\ (w_L - 7)$	[1]
$C_c = 0.007\ (w_L - 10)$: Remolded clays $C_c = 0.009\ (w_L - 10)$: Undisturbed clays	[2]
$C_c = 0.29\ (e_0 - 0.27)$	[3]
$C_c = 0.43\ (e_0 - 0.25)$	[7]
$C_c = 0.02 + 0.014 I_P$	[8]
$C_c = 0.01\ (w_0 - 5)$	[9]
$C_c = 0.5 I_P G_s$	[10]
$C_c = 0.015\ (w_L - 19)$	[11]
$C_c = 0.01\ (w_0 - 7.55)$	[12]
$C_c = 0.2237 e_L$	[13]
$C_c = 0.2343 e_L$	[14]
$C_c = 0.274 e_L$	[15]
$C_c = 0.156 e_0 + 0.0107$	[16]
$C_c = 0.007(I_s + 18)$	[17]
$C_c = 0.0103 w_0$	[18]
$C_c = 0.015 I_P - 0.0198$	[19]
$C_c = \frac{n_0}{371.747 - 4.275 n_0}$	[20]

Note: C_c, compression index; w_L, liquid limit; e_0, initial or in situ void ratio; I_P, plasticity index; w_0, initial or insitu water content; G_s, specific gravity; e_L, void ratio at liquid limit; I_s, shrink limit; n_0, insitu porosity.

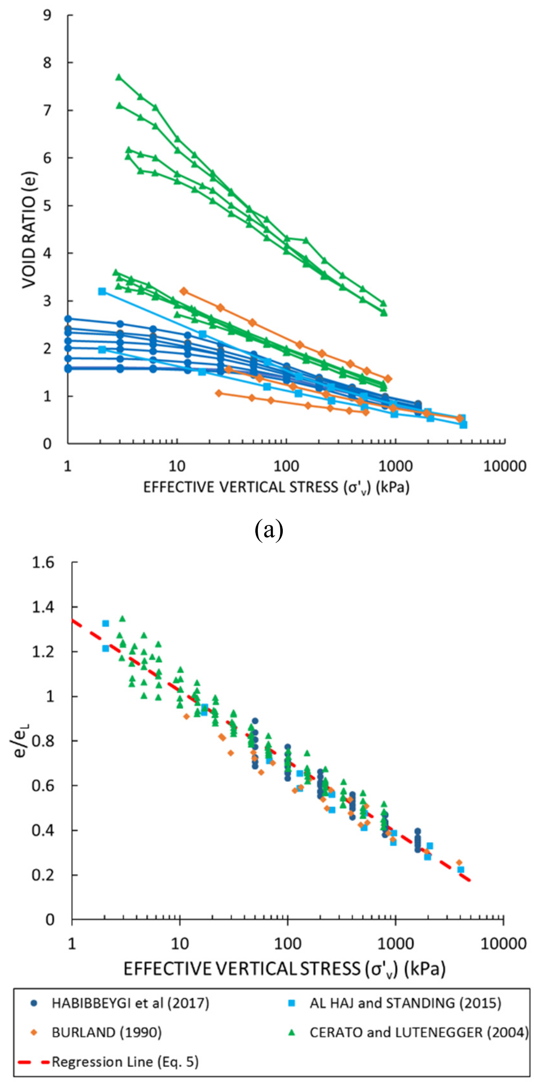
Most empirical relations are supposed to estimate a soil compression index under a wide range of conditions. However, representing a unique equation to reliably estimate the compression index (C_c) for all types of soil classifications and soil states is almost impractical due to the complexity of soil structures, mineralogy, and inevitable sample disturbance. Thus, any suggested equation must be used carefully and be suited to the relevant soil conditions. In fact, the assessment of the compression index (C_c) for a clayey soil (which is determined by laboratory oedometer tests) is highly influenced by the soil state. Another parameter that affects the compression behaviour of clays is the sampling procedure. Sampling disturbance has an especially great impact on sensitive clays with compression curves that are no longer linear. It is now well established that compression curves for reconstituted clays are non-linear [21, 22]. However, there are several different relationships used to link compression index to consistency limits, and only a few have been developed especially for high level of moisture content. To the authors' knowledge, there is also a lack of experimental data for predicting the compression index of a soil with high initial water content. In the present paper, a new equation for estimating the compression index of reconstituted clays is proposed, using the intrinsic and normalisation concepts. First, a regression normalisation line is proposed based on the results of one-dimensional consolidation tests on four studies that were performed on reconstituted clays. Then an empirical equation is derived by using the equation of normalisation line as well as the theoretical criterion for shear strength at consistency limits proposed by Wroth and Wood, 1978 [10]. Finally, the derived equation is validated using a broader range of data available from the literature regarding clayey soils with different mineralogy, soil conditions and soil classifications to evaluate the applicability of the equation to other clays.

2. NORMALIZING COMPRESSION CURVES OF RECONSTITUTED CLAYS

The concept of using void ratio at the liquid limit to normalise compression results was originally proposed by Nagaraj and Murthy, 1983, 1986 [13, 23]. In this study, nineteen series of compression data from seven different reconstituted clays were used to plot normalised compression curves (graph of normalised void ratio versus effective vertical stress) within the stress range of 50—2000 kPa. Geotechnical parameters, such as consistency limits and specific gravity values from the consolidation database, are tabulated in Table 2. Liquid and plastic limits (w_L, w_P) of the studied soils ranged from 42% to 200% and 23% to 108%, respectively; plasticity indexes (I_P) varied broadly, from 16 to 94; specific gravity (G_s) ranged from 2.60 to 2.83. Compression curves of the investigated soils are presented in Fig.2 (a) in the form of void ratio versus effective vertical stress in a semi-logarithmic plane. Consolidation data is also normalised in Fig.2 (b) using normalised void ratio (e/e_L). As illustrated in Fig.2 (b), for consolidation stresses greater than 50 kPa, compression curves are confined within a narrow band of e/e_L against vertical consolidation stress (σ_v') in a semi-log plane. Moreover, the equation of the narrow band can be fitted with a straight line with an acceptable correlation coefficient ($R^2 = 0.96$) as follows:

$$e/e_L = 1.3402 - 0.3162 \log \sigma_v' \qquad (5)$$

where e is the void ratio, e_L is the void ratio at the liquid limit, and σ_v' is the effective vertical stress in kPa.



(b)

Fig. 2 Compression curves in semi-logarithmic space, data extracted from references [22, 24-27]

(a) e - $\log \sigma_v'$ space
(b) Normalised compression curves in e/e_L-$\log \sigma_v'$ space

Table 2 Geotechnical parameters of the studied soils

Soil Description	w_L (%)	w_P (%)	I_P (%)	G_s	Reference
Kleinbelt Ton	127	36	91	2.77	[24]
London clay	67	27	40	2.71	[24]
Wiener Tegel	47	22	25	2.76	[24]
Black soil	60	30	30	2.72	[25]
Red soil	87	33	54	2.78	[25]
Kaolinite	42	26	16	2.68	[26]
Boston Blue clay	45	23	22	2.80	[26]
Atchafalaya	101	35	66	2.80	[26]
Attapulgite	202	108	94	2.83	[26]
Baldivis clay	82	35	47	2.60	[22]

The compression curves of the reconstituted clays presented in Fig.2(b), are replotted in Fig. 3 using the intrinsic framework. The 'intrinsic concept' was first termed by Burland, 1990 [24] for correlating the inherent compression curves of reconstituted clays and was widely used afterwards by other researchers to present the compression behaviour of clays. Burland, 1990 [24] introduced an 'Intrinsic Compression Line' (ICL), which is derived by plotting the void index (I_v) against vertical stress in a semi-log plane to study the compression behaviour of reconstituted clays. The void index (I_v) used in the intrinsic concept is defined as follows:

$$I_v = \frac{e - e^*_{100}}{e^*_{100} - e^*_{1000}} \quad (6)$$

where the values of e^*_{100} and e^*_{1000} are the void ratios of the vertical stresses at 100 kPa and 1000 kPa, respectively. Burland, 1990 [24] also proposed a polynomial equation to express the unique intrinsic compression line (ICL) in terms of effective vertical consolidation stress at a range of liquid limits varying widely between 25 and 128%:

where σ'_v is the effective vertical stress

$$I_v = 2.45 - 1.285(\log \sigma'_v) + 0.015(\log \sigma'_v)^3 \quad (7)$$

expressed in KPa. The equation for the ICL (Equation 7) can be used for a range of stresses between 10 and 4000 kPa.

The ICL can normalise the virgin compression curves of a clayey soil reasonably well for medium to high levels of vertical consolidation stress [22]. Although there is an impact of initial water content on the compression behaviour of reconstituted clays at low stress levels [21, 22], both methods of normalisation, i.e. void index and normalised void ratio at the liquid limit, plot the compressibility of reconstituted clays in a narrow band as vertical consolidation stress increases (greater than 50 kPa). The relation of the void index (Fig. 3) can be expressed by a linear regression, with a correlation coefficient of 0.98, of the form:

$$I_v = 2.142 - 1.055(\log \sigma'_v) \quad (8)$$

As seen on Fig. 3, in the range of studied stresses, a good agreement exists between the ICL proposed by Burland, 1990 [24], Eq. 7, and the regression line proposed in this study (Eq. 8). Although there is a slight disparity at stress levels higher than 2000 kPa, the proposed equation almost coincides with Burland's results for stresses between 50—2000 kPa. Similarly, Horpibulsuk et al, 2016 [27] proposed that virgin compression curves using an intrinsic framework are nearly unique for stresses higher than 100 kPa. However, this boundary stress can be reduced to 50 kPa for clayey soils with high initial water content to reflect a wider range of stress. In fact, the aforementioned linear regression equations can be used to express the compressibility of reconstituted clays above the A-line of plasticity chart, which is the soil type considered in this study.

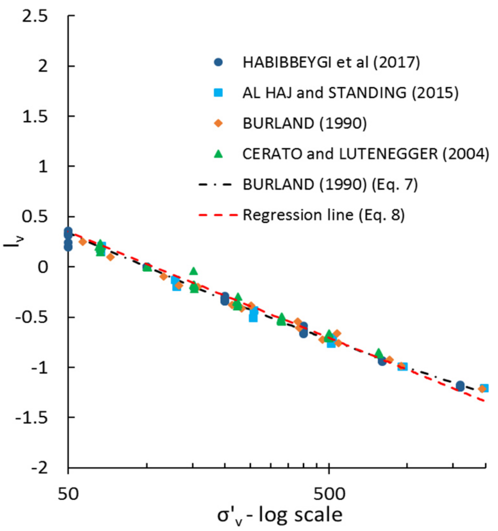


Fig. 3 Normalised compression curves in I_v-log σ'_v space

3. DETERMINING COMPRESSION INDEX

Skempton and Bishop, 1954 [28] showed that a relationship exists between the shear strength of clayey soils and their liquid limit. Moreover, it is now well-established that the shear strength of all clayey soils at water contents near the liquid limit is consistently 1.7 kPa [10, 29-31]. Wroth and Wood, 1978 [10] also reported that the major principal effective vertical stress in a normally consolidated soil is almost constant for all types of fine grained soils and is equal to 6.3 kPa at the liquid limit. Furthermore, according to Wroth and Wood, 1978 [10], the shear strength of a clayey soil at its plastic limit is approximately 100—150 times the correlated shear strength at its liquid limit. Therefore, it can be presumed that the stress at the plastic limit of a clayey soil would be 100—150 fold greater than the related vertical stress at its liquid limit (6.3 kPa), i.e. approximately 800 kPa. This assumption will be verified later in this paper by testing the reliability of the estimated compression index values by comparing them with measured values. The compression index (C_c), by definition, is the slope of the compression curves in a semi-log plane (Fig. 4):

$$C_c = -\frac{\Delta e}{\Delta \log \sigma'_v} = \frac{e_1 - e_2}{\log \sigma'_{v_2} - \log \sigma'_{v_1}} \tag{9}$$

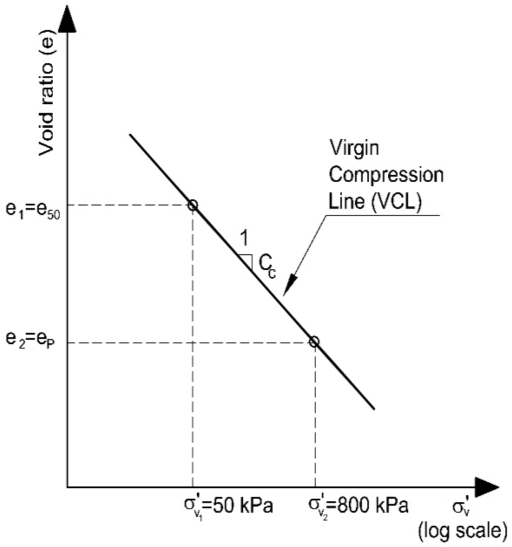


Fig. 4 Schematic graph of compression index calculation

As shown by both methods of normalisation, the relationship between void ratio invariants (void index (I_v) and normalised void ratio (e/e_L)) and vertical stress is linear beyond 50 kPa for the primary consolidation stage. Thus the void ratio at a vertical stress of 50 kPa (e_{50}), has been chosen as the first point for calculating the slope of the virgin compression line. The second point chosen for slope calculation, based on Wroth and Wood, 1978 [10], is the void ratio at the plastic limit (e_P) and its corresponding vertical stress of 800 kPa. By substituting the void ratios at a vertical stress of 50 kPa and at the soil plastic limit (e_{50}, and e_P) , and their related vertical stresses (50 kPa and 800 kPa) into Eq. 9, the compression index can be expressed in the form:

$$C_c = \frac{e_{50} - e_P}{\log 800 - \log 50} = 0.830\,(e_{50} - e_P) \tag{10}$$

By using the regression equation (Eq. 5), e_{50} can be written using the void ratio at the liquid limit e_L, and the compression index can be written in the form:

$$e_{50} = 0.803 e_L \tag{11}$$

$$C_c = 0.666 e_L - 0.830 e_P \tag{12}$$

Equation (12) suggests that the compressibility of a reconstituted clay is exclusively a function of the soil void ratio at its consistency limits. By replacing the void ratio with water content using the equation $w.G_s = S_r.e$ (where w is the water content, G_s is the specific gravity, and S_r is the degree of saturation), Eq. 12 can be rewritten for consistency limits in a saturated condition (S_r = 100%) by taking into account the average specific gravity for clays (2.6) in the form:

$$C_c = 0.0173 w_L - 0.0216 w_P \tag{13}$$

Ninety-two consolidation tests conducted under various mineralogy and soil conditions, and reported in the literature, were used as an independent database to estimate compression indexes using Eqs. 12 and 13. Results were then compared with values measured from consolidation tests, to validate the efficiency of the proposed relationships. The results of this comparison are presented in Fig. 5, which shows a reasonable agreement between the predicted values and the measurements reported in the literature. As discussed before, a unique relation exists between consolidation stress and plastic limit [10, 29]. The result of this study also suggests that the assumption of the mean vertical consolidation stress at the plastic limit being 125 times that at the liquid limit is acceptable for the studied soils. Hence, it can be concluded that void ratios at 50 kPa and at the plastic limit can be employed for determining the compression index of reconstituted clays with acceptable accuracy.

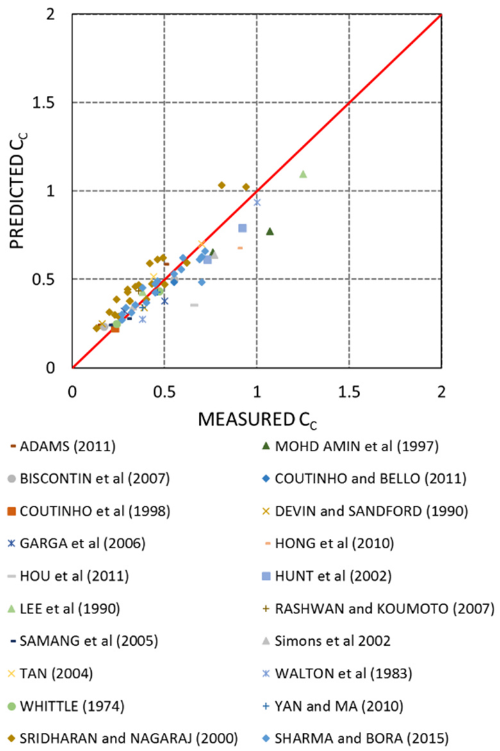


Fig. 5 Comparison between estimated and measured compression indexes (data extracted from Ref. [17, 21, 32-49])

4. CONCLUSIONS

Compression curves of normally consolidated reconstituted clays were normalised in the present paper using two methods of normalization, i.e. void ratio and void ratio at liquid limit (e_L). Both methods show that the consolidation curves (e-$\log\sigma_v'$) are linear at stresses between 50—2000 kPa. It has also been shown that consolidation stress at the plastic limit can be assumed to be about 125 times greater (i.e. 800 kPa) than the correlated consolidation stress at the liquid limit based on the theoretical criteria proposed by Wroth and Wood, 1978 [10]. This unique point on the compression curve together with the point associated to a void ratio at 50 kPa (e_{50}) were used to estimate the compression index of reconstituted soils. In fact, the compression index was found to be a unique function of the consistency limits (i.e. liquid limit w_L and plastic limit w_P) for saturated reconstituted clays over the A-line in the plasticity chart. Based on these findings, an equation was proposed that uses consistency limits to estimate the compression index of reconstituted clays. The accuracy of the estimates was verified by comparison with a broad range of measured data from the literature. Findings indicate that the equation proposed in this study is suitable to predict the compression index of reconstituted clays above the A-line in the plasticity chart, with reasonable accuracy.

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