Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0498

Compressibility of Finnish sensitive clay

Compressibilité des argiles sensibles finlandaises

Bruno Di Buò
Tampere University of Technology, Tampere, Finland

Tim Länsivaara
Tampere University of Technology, Tampere, Finland

Andrea Franza
Universidad Politécnica de Madrid, Madrid, Spain

Paul Mayne
Georgia Institute of Technology, Atlanta, USA

ABSTRACT: Tampere University of Technology (TUT) and Finnish Transport Agency (FTA) have been conducting an extensive field and laboratory experimental program aiming to evaluate the strength and deformation properties of Finnish sensitive clay. This paper presents a detailed investigation of the compressibility parameters with particular emphasis on the empirical correlations with the index properties. The traditional method used to describe the compressibility of natural clay is based on the compressibility indices (e.g., C_c, C_r) which are determined by means of 1-D consolidation tests. However, this method is not suitable to describe the compressibility of sensitive clays due to the nonlinear stress-strain behaviour beyond the preconsolidation stress (σ'_p) shown in the semilogarithmic scale. For this reason, an alternative method for evaluating the soil compressibility based on a power law equation is presented. These methods are compared and empirical correlations between the compressibility parameters and soil index properties are established.

RÉSUMÉ: L'Université de technologie de Tampere (TUT) et l'Agence de transport finlandaise (FTA) ont mené un vaste programme expérimental sur le terrain et en laboratoire visant à évaluer les propriétés de résistance et de déformation de l'argile sensible finlandaise. Cet article présente une étude détaillée des paramètres de compressibilité avec un accent particulier sur les corrélations empiriques avec les propriétés de l'indice de réfaction. La méthode traditionnelle utilisée pour décrire la compressibilité de l'argile naturelle est basée sur les indices de compressibilité (par exemple, C_c, C_r) qui sont déterminés au moyen d'essais de consolidation à une dimension. Cependant, cette méthode ne convient pas pour décrire la compressibilité des argiles sensibles en raison du comportement non linéaire du rapport contrainte-déformation au-delà de la contrainte de préconsolidation . Pour cette raison, une méthode alternative est présentée; Basée sur une équation de la loi de puissance, elle permet d'évaluer la compressibilité du sol. On comparera les différentes méthodes grâce à des corrélations empiriques entre les paramètres de compressibilité et les propriétés de l'indice de sol.

Keywords: compressibility; deformation; settlement; oedometer; sensitive clays

1 INTRODUCTION

The volume change in clayey soils represents one of the most important problems in geotechnical engineering since it may induce severe damages to structures and infrastructure located on the soil deposit. The application of a load determines a delayed volumetric response due to the interaction between the soil skeloton and the porewater. This process is generally referred to "consolidation" and indicates the time-dependent volume change due to the excess pore pressure dissipation. The investigation of this phenomenon is fundamental in the geotechnical design, especially when the soil settlement results in severe damage to the structures and infrastructures.

The present study aims to investigate the compressibility of Finnish sensitive clay. It has been observed that the marine clays located in Scandinavia and Canada are characterized by high compressibility and low bearing capacity, which represent significantly problematic engineering properties in terms of settlement and stability (Leroueil 1983).

One-dimensional consolidation theory (Terzaghi 1951) is the most commonly employed method to evaluate settlements in natural clays. The calculation is generally performed by using two parameters: the virgin compression index (C_c) and the recompression (or swelling) index (C_r). These parameters are determined by using graphical methods applied to the 1-D oedometer test result. However, soil sampling and laboratory consolidation tests require a great deal of time and cost. For this reason, establishing reliable trasformation models would give the possibility to perform preliminary calculations as well as filling the information between oedometer test results. Various correlations between the compression index and the soil properties, such as the natural water content (w_n), initial void ratio (e_0), liquid limit (w_L) and plasticity index (PI) have been proposed over the past decades. However, these studies generally referred to a particular soil condition, and therefore their use require further validation and, possibly, local calibration when applied to soils with different properties and geologic settings.

In this paper, a series of constant rate of strain (CRS) oedometer tests carried out on undisturbed samples have been exploited to investigate the compressibility of the Finnish sensitive clays. Regression analyses are performed to establish empirical correlations for the estimation of C_c and C_r based on their soil index properties.

Finally, an alternative method to describe the compressibility of Finnish sensitive clay in the normally consolidated region is presented. The validity of the two methods is assessed by comparing the experimental stress-strain behaviour with the predicted ones.

2 EXPERIMENTAL PROGRAM

Field and laboratory data were collected from four soft sensitive clay test sites located in Finland (S_t=20–100). The main geotechnical properties of the investigated clays are summarized in Table 1.

The experimental program includes CRS oedometer tests, classification, and index tests.

A total of 83 constant rate of strain (CRS) oedometer tests were carried out on undisturbed samples with 45 mm diameter and 15 mm height. The strain rate used for the testing is 0.001 mm/min (0.4 %/h). Further details about sample quality and oedometer test results are presented by Di Buò et al. (2018b).

Table 1. Geotechnical properties of investigated sites

Site	z (m)	w (%)	PI	OCR
Perniö	2 – 3	110	40	2
	3 – 6	80 – 90	20	1.5
	6 – 8	100	40	1.3
Masku	3	80 – 90	40	1.5 – 1.7
	5	120	70	1.5
	8	70 – 80	40	1.2 – 1.5
Paimio	3 – 6	50 – 80	20	1.6 – 1.8
	6 – 9	100	40	1.3 – 1.4
Sipoo	2 – 4	80 – 90	45	1.7 – 1.9
	4 – 9	100 – 120	55	1.3 – 1.5

3 COMPRESSION INDEX METHOD

The compression index (C_c) represents the slope of the virgin compression curve while the recompression index (C_r) refers to the slope of the recompression or swelling curve. These parameters describe the variation of the void ratio e as a function of the change of vertical effective stress σ'_v plotted in the logarithmic scale. They are defined as:

$$C_{c,r} = -\frac{\Delta e}{\Delta log \sigma'_v} \quad (1)$$

The results of 1-D consolidation test conducted on Pisa clay are presented in Fig. 1. As shown, $C_{c,r}$ can both be assumed as constant values since the behaviour in the semilogarithmic scale is linear. This is common for insensitive clays while some difficulties arise for sensitive clays.

3.1 Overview of existing empirical correlations for compression index

As discussed earlier, the evaluation of the compression index based on the consolidation tests is time-consuming. Furthermore, the adopted graphical methods are highly influenced by the quality of the tested samples. Because of these issues, empirical correlations have been proposed to determine the compressibility parameters based on their index properties. Existing equations are mainly correlated to the state variables (e_0, w_n) and intrinsic variables (w_L, *PI*, clay mineralogy). Table 2 presents a summary of some selected existing correlations for evaluating the C_c and modulus number (m).

Table 2. Empirical correlations for C_c

Proposed Equation	**Reference**
C_c=0.007(w_L-10)	Skempton (1944)
C_c=0.017(w_L-20)	Shouka (1964)
C_c=(w_L-13)/109	Mayne (1980)
C_c=0.01w_n	Koppula (1981)
C_c=0.85(w_n/100)$^{1.5}$	Helenelund (1951)
C_c=0.01(w_n-7.549)	Herrero (1983)
m=2.3(1+e_0)/C_c=700/w_n	Janbu (1985)

Natural clays are generally characterized by a wide range of C_c values, varying between 0.1 – 1 for medium soft clays, while values higher than 3 are observed for highly sensitive clays (Lancellotta, 2014). Since this range is quite high, the applicability of these equations is usually limited to particular soil conditions.

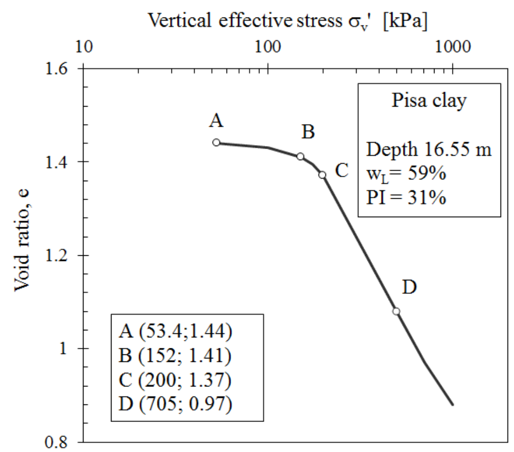

Figure 1. 1-D consolidation test result, Pisa clay (Lancellotta, 2014).

3.2 Compressibility of Finnish sensitive clay

The behaviour of Finnish sensitive clay is the typical response of lightly overconsolidated marine clays described by Janbu (1985). From the oedometer test results (Fig. 2) conducted on Perniö clay, it is possible to notice distinct pre-yielding (overconsolidated region, OC) and post-yielding (normally-consolidated region, NC) behaviours. The transition between these two regions is defined by the preconsolidation stress (σ'_p). In particular, this transition is characterized by an evident drop due to destructuring of the microstructure and interparticle bonding induced by the applied load. Figure 2b shows the oedometer test results in terms of the void ratio versus the vertical effective stress (e vs. σ'_v) in semilogarithmic scale. It is evident that while the recompression index C_r can be easily determined, the evaluation of C_c appears more difficult due to the nonlinearity in the normally consolidated (NC) region as shown in Fig. 2b. For this reason, the method using the compression index is generally considered unsuitable for representing the compressibility of sensitive clays. Many authors have proposed alternative methods such as the tangent modulus method (Janbu 1963) and the Swedish method (Sällfors, 1975) which are the more commonly used methods in the Nordic countries for the settlement calculation in soft clays.

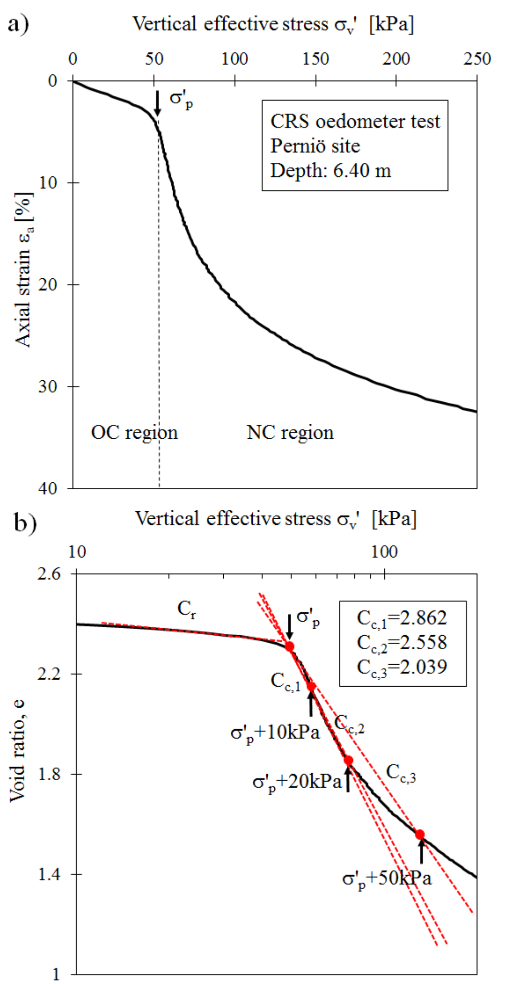

Figure 2. CRS oedometer test result from Perniö site: a) vertical effective stress versus axial strain; b) graphical method adopted to evaluate the compression index applied to the plot vertical effective stress versus void ratio.

In this study, the validity of the compression index method is assessed for the investigated clay. In particular, three different parameters are considered: $C_{c,1}$, $C_{c,2}$, and $C_{c,3}$ referred to σ'_p+10 kPa, σ'_p+20 kPa, and σ'_p+50 kPa, respectively. The graphical method used for the determination of these parameters is presented in Fig. 2b.

3.2.1 Compressibility vs state variables

Various researchers have pointed out that the evaluation of compression index of natural clays based on intrinsic variables (w_L, *PI*) is misleading since the compressibility is mainly influenced by the sedimentation state induced by the deposition environment (Schmertmann 1955; Burland 1990; Lee et al 2016). For this reason, empirical correlations based on the state variables (e_0, w_n) are considered more effective. In this study, the regression analyses were conducted on both w_L and w_n.

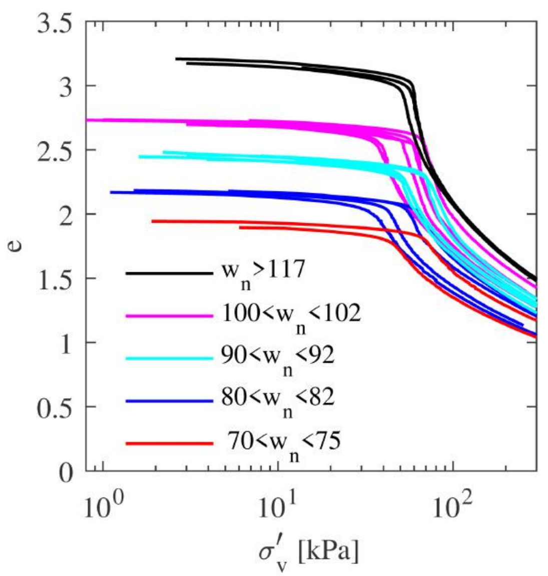

Figure 3. Influence of the water content (w_n) on soil compressibility.

The influence of w_n on the compressibility of sensitive clays has been deeply investigated (Janbu 1963; Helenelund 1951). In particular, samples characterized by higher w_n tend to be more compressible. Figure 3 presents a summary of CRS oedometer test results conducted on Finnish sensitive clays for different water content ranges. It is worth noting that the soil compressibility increases with the water content as observed in previous research studies.

The outcomes of the regression analysis between the compression/recompression index and the water content are shown in Fig. 4. Values for the recompression index range from 0.1 to 0.3, while the compression indices vary from 1 to 7. Regression results illustrate that there is a clear link between the parameters C_c and the water content while high scatter in data is observed for the magnitude of C_r. However, since the soil compressibility observed in the OC region is relatively smaller than in the NC region (C_r<<C_c), the accuracy in the determination of C_r does not considerably influence the total settlement calculations.

3.3 *Compressibility vs intrinsic variables*

The intrinsic variables (w_L, *PI*, clay mineralogy) are related to the particles properties and their distribution. As discussed earlier, empirical correlations based on these parameters are not considered suitable for deriving the compressibility parameters. However, various relationships have been proposed in the literature (Table 2) mainly based on the liquid limit and plasticity index.

In this paper, the influence of the w_L on the soil compressibility parameters were confirmed. Figure 5 presents the plot of C_c versus the liquid limit w_L. The charts are characterized by evident data scatter for both the compression and recompression indices. In addition, larger scatter was observed when considering other intrinsic variables (e.g., *PI*, clay content); thus, a clear link between the intrinsic variables and the soil compressibility could not be verified by the Authors for the investigated clays. This confirms that the compressibility of sensitive clays are only weakly related to intrinsic variables since these parameters are not able to reliably describe the soil sedimentation state.

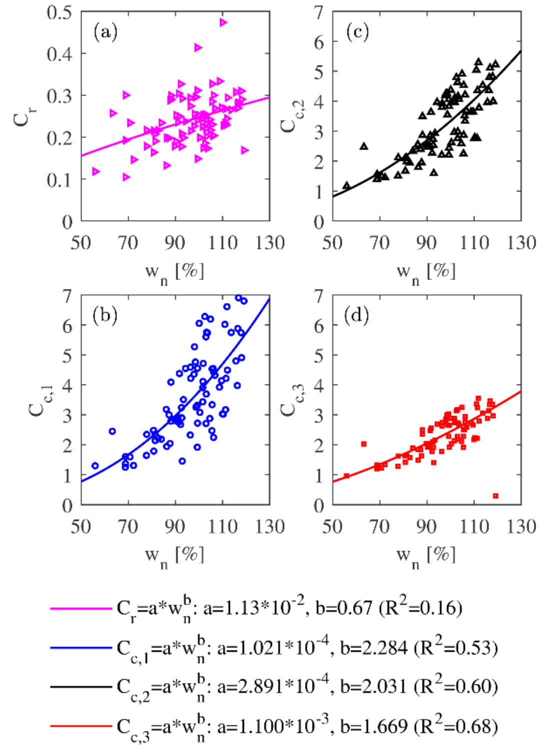

Figure 4. Regression analysis between the compression indices (C_c, C_r) and water content for Finnish clays.

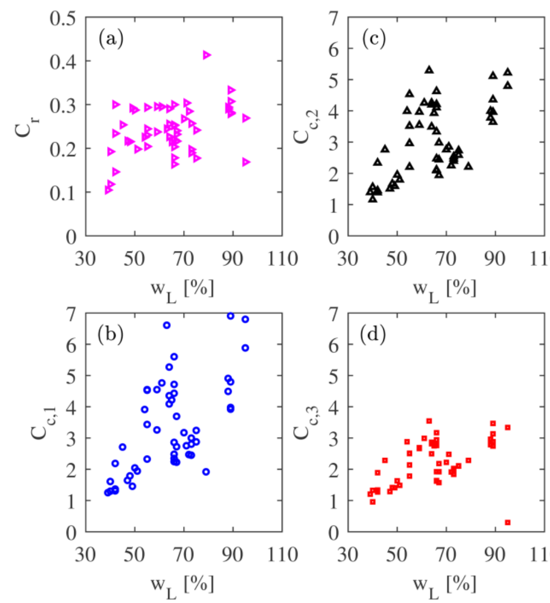

Figure 5. Influence of the liquid limit (w_L) on the compressibility of Finnish clays.

4 POWER LAW METHOD

Differently from what has been observed for insensitive natural clays (Fig. 1), the compression index C_c of sensitive clays is not adequately represented as a constant value due to the nonlinear behaviour in the NC region presented in the semilogarithmic scale. The possibility of considering a limited stress range beyond the preconsolidation stress can partially overcome this issue despite an incomplete description of the soil compressibility.

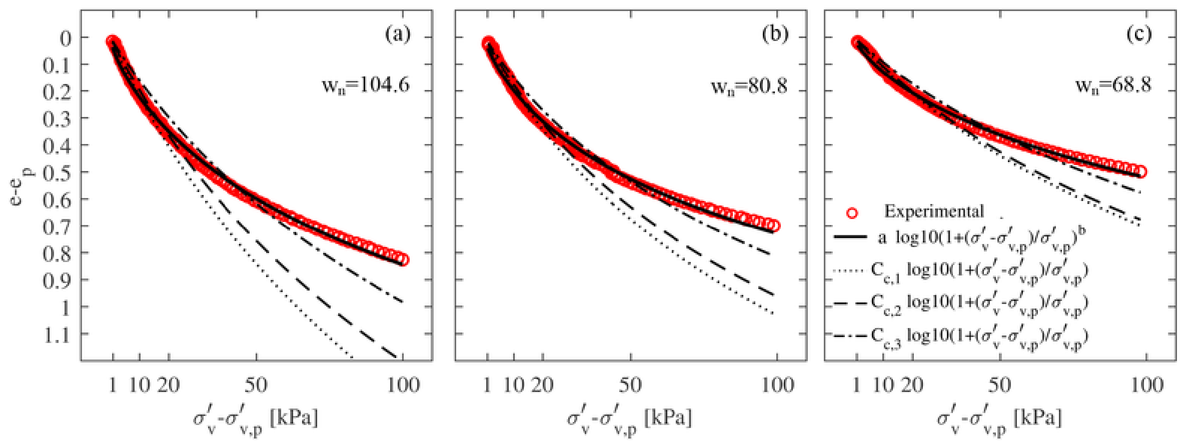

Figure 6. Comparison between the index method and the power law method prediction with experimental data.

As an alternative method, it is proposed that the nonlinear stress-strain behaviour in the NC region can be approximated by the following power law equation defined as:

$$\Delta e = \left| e - e_p \right| = a \log\left(1 + \frac{\sigma'_v - \sigma'_p}{\sigma'_p}\right)^b \qquad (5)$$

where e_p is the void index at the preconsolidation stress σ'_p, σ'_v is the vertical effective stress, and a and b are empirical fitting parameters. Figure 6 shows the comparison between the experimental results and the empirical estimations provided by the two methods for three representative tests characterized by different w_n. As expected, the compression index method provides an acceptable estimation of the soil compressibility at low stress levels. In contrast, the power law method gives a rather good fitting of the experimental data for all the NC range, for stress up to σ'_p+100 kPa. Such behaviour has been observed for all the oedometer tests available. The investigation conducted on the fitting parameters revealed that the water content plays an important role. In particular, the coefficient a ranges between 0.6 and 2.2, assuming higher values with increasing w_n. In contrast, the fitting parameter b varies between 0.5 and 1, with lower values at high w_n. Preliminary correlations for the evaluation of a and b based on the water content are presented in Fig. 7. However, further investigation is needed to clearly understand the nature of these coefficients and their dependency with other soil properties.

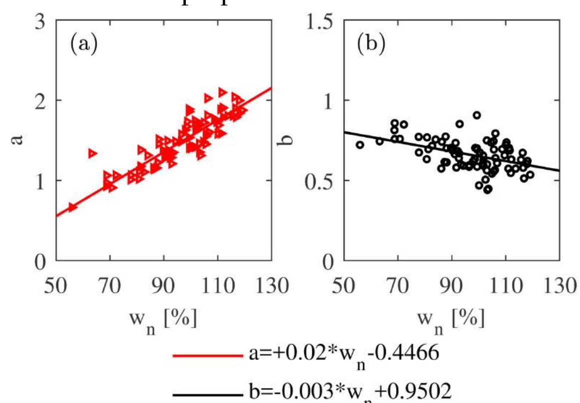

Figure 7. Power law parameters a and b plotted versus w_n.

5 CONCLUSIONS

The investigation conducted in this study aimed to evaluate the compressibility properties of sensitive Finnish clays taken from four sites. A database of 83 CRS oedometer tests carried out on high quality undisturbed samples is exploited to evaluate the compressibility of Finnish clays. In particular, the traditional compression index method turns out to be poorly suited when applied to sensitive clays. The main reason for this observation lies in the definition of the compression index C_c and C_r, which are generally assumed as constant values in natural clays of low-medium sensitively.

Different from "well-behaved" clays, sensitive clays are characterized by highly nonlinear stress-strain behavior for stress levels beyond the preconsolidation stress as observed in the semilogarithmic scale plot (Fig. 2b). Therefore, the validity of the compression index method is highly influenced by the stress range selected to define the compression index. The comparison with experimental data confirms that the method provides a fair estimation of the soil compressibility at relatively low stress levels. Finally, correlations are derived to evaluate the C_c based on the water content while scatter of data are noticed for the recompression index C_r.

In order to overcome the above issues, a new method based on a power law equation is proposed in the study. It was observed that the model predictions agree with the experimental data for all normally consolidated (NC) regions. The method appears to have a good potential in estimating settlements in sensitive clays. Further evaluation is required to investigate the validity in different soil conditions (e.g., Scandinavia and Canada) and to establish correlations between the parameters of the power law equation and soil index properties. Moreover, a direct comparison with existing settlement calculation methods (e.g., Janbu method and Swedish method) is needed to establish which method is more suitable for the evaluating the deformation properties and to estimate magnitudes of settlement in sensitive clays.

6 BIBLIOGRAPHY

Burland, J.B. 1990. On the compressibility and shear strength of natural clays. *Géotechnique*, 40(**3**), 329-378.

Di Buò, B., D'Ignazio, M., Selänpää, J., & Länsivaara, T. 2016. Preliminary results from a study aiming to improve ground investigation data. In *Proceedings of the 17th Nordic Geotechnical Meeting: Challenges in Nordic Geotechnics*, Reykjavik, Iceland, 25-28 May 2016. Icelandic Geotechnical Society.

Di Buò, B., Selänpää, J., Lansivaara, T.T., & D'Ignazio, M. 2018a. Evaluation of existing CPTu-based correlations for the deformation properties of Finnish soft clays. In *Cone Penetration Testing IV: Proceedings of the 4th International Symposium on Cone Penetration Testing (CPT 2018)*, June 21-22, 2018, Delft, The Netherlands.

Di Buò, B., Selänpää, J., Länsivaara, T., & D'Ignazio, M. 2018b. Evaluation of sample quality from different sampling methods in Finnish soft sensitive clays. *Canadian Geotechnical Journal*. https://doi.org/10.1139/cgj-2018-0066

Helenelund, K.V. 1951. Om konsolidering och sättning av belastade marklager: On consolidation and settlement of loaded soil-layers. Diss. Tekniska högskolan, Helsingfors.

Herrero, O.R. 1983. Closure to: Universal compression index equation. *Journal of the Geotechnical Engineering Division*, ASCE 109(**5**): 755–761.

Janbu, N. 1963. Soil compressibility as determined by oedometer and triaxial tests. In *Proc. Europ. Conf. SMFE* (Vol. 1, pp. 19-25).

Koppula, S.D. 1981. Statistical estimation of compression index. *Geotechnical Testing Journal 4(2):* 68-73.

Lancellotta, R. 2014. *Geotechnical Engineering*. CRC Press, London: 520 pages.

Lee, P. T., Tan, Y. C., Lim, B. L., Nazir, R. 2016. Some geotechnical properties of Tokai clay. *Proceedings of the 19th Southeast Asian Geotechnical Conference*. Malaysia: 1–5.
Leonards, G.A., and Altschaeffl, A.G., 1964. Compressibility of clay, *Journal of the Soil Mechanics and Foundations Division*, ASCE, 90, SM5. 133-155.
Mayne, P.W. 1980. Cam-clay predictions of undrained strength. *Journal of Geotechnical Engineering*, ASCE 106(11): 1219–1242.
Sällfors, G. 1975. *Preconsolidation pressure of soft, high-plastic clays*. Doctoral dissertation, Chalmers University of Technology.
Shouka, H. Relationship of compression index and liquid limit of alluvial clay. *Proceedings of the 19th Japan Civil Engineering Conference.* Touhoku. 1964.
Schmertmann, J.H. 1955. The undisturbed consolidation behaviour of clay. Trans. ASCE, 120, 1201-1233.
Skempton, A.W. and O.T. Jones. 1944. Notes on the compressibility of clays. *Quarterly Journal of the Geological Society* 100.1-4: 119-135.
Terzaghi, K. 1951. *Theoretical Soil Mechanics*. Chapman and Hall, Limited.; London.