Determination of Virgin Compression Destructuring Line Parameters for Natural Clays

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ABSTRACT: Based on the destructuring framework proposed by Liu et al. (2015) preceded by the work by Liu and Carter (1999, 2000), the virgin compression destructuring behavior of fifteen natural soil published in various literature over the last seven decades in several locations around the globe have been studied. Two methods (i.e., graphical and two reference point approach) to determine the parameters used in the equation of compression destructuring line (CDL) are proposed and examined by simulating the experimental data. Also, a systematic approach to find the yield pressure is suggested. The study concluded that CDL parameters obtained from graphical approach successfully predicted the compression behaviors of structured soil for most of the soil samples. Nonconformity occurs in case of two reference point approach in some cases. The two reference point approach is very helpful for a quick approximation of the CDL parameters because of its simplicity. Theoretically, two reference point method should be independent of the selection of the two point sets and always yield the same parameters but due to the uncertainty of the precision of experimental data, it varied. The author used and suggested a universal by taking furthest two points on the destructuring compression data as references. Also, the analytical approach to locate the yield pressure point is found very helpful. These methods eliminate the rigorous process of trial and error to find CDL parameters and other conventional processes to locate the yield pressure.

Keywords: Structured soil, Soil destructuring, Compression destructuring line, Yield pressure, Compression destructuring index

1. INTRODUCTION

The compression behavior of soils in its natural state differs from its remolded state due to the presence of soil structure as a result of particle arrangement, cementation, aging and overcompression (Burland, 1990; Graham and Li, 1985; Leroueil et al., 1979; Mitchell, 1976; Skempton and Northey, 1952). This compression behavior of structured soil can be classified into two states: (1) the intact state wherein the structure is intact and behaves elastically and easy to predict and (2) the destructuring state in which the breakdown of structure in soils occur. These two states coincide at a point known as the yield pressure. The later state is hard to predict and received considerable attention in the last three decades. Various models have been proposed to define the nonlinear normal compression line (i.e., destructuring state) named here as compression destructuring line (CDL) by several researchers which can be broadly classified among four groups. (1) stepped or zig-zag approximation (Burghignoli et al., 2010; Gens and Nova, 1993; Lagioia and Nova, 1995) (2) bi-logarithmic method (Butterfield, 1979; Chai et al., 2004; Hong et al., 2012) (3) power function (Li et al., 2015; Liu and Carter, 2000; Liu et al., 2005; Liu et al., 2015) and (4) differential function (Yang et al., 2014). Each of the methods has their own merits and limitations. This study is limited to the power function to define the compression destructuring line of natural soils based on the framework proposed by Liu et al. (2015).

Liu and Carter (1999) proposed a simple equation to predict virgin compression behavior of structured soils. Liu et al. (2015) followed by the work of Liu and Carter (1999; 2000) proposed a general equation to model the destructuring of a variety of structured soils with a power equation. There is no direct suggestions or proposal besides trial and error to find the parameters used in the power function. Also, the traditional graphical method has been followed to locate yield pressure.

This paper aims to develop a more direct approach to define the Compression Destructuring Line (CDL) of natural soils based on power function. Rational approaches to find the exponent and other constant term used in the equation of CDL have been proposed and compared. An analytical method to locate the yield pressure has also been proposed. The compression data for different soils published in different papers in their natural and remolded state are used to compute these values.

2. THEORETICAL FRAMEWORK FOR STRUCTURED SOIL DURING VIRGIN COMPRESSION

An ideal compression behavior in $e - \ln p'$ space of a naturally structured soil and same soil without its structure used as reference is shown in Figure 1. The virgin compression of soil after reconstitution is assumed to be the reference behavior of same soil without its structure. The properties of reconstituted soil are called intrinsic soil properties and denotes by asterisk (*) as suggested by Burland (1990).

The void ratio, e of a structured soil as suggested by Liu and Carter (1999; 2000) at any mean effective pressure, p' can be expressed as the summation of the corresponding void ratio for the same soil without structure, e^* named as intrinsic void ratio of reconstituted soil and the additional void ratio due to structure, Δe termed here as structured void ratio. Hence,

$$e = e^* + \Delta e \tag{1}$$

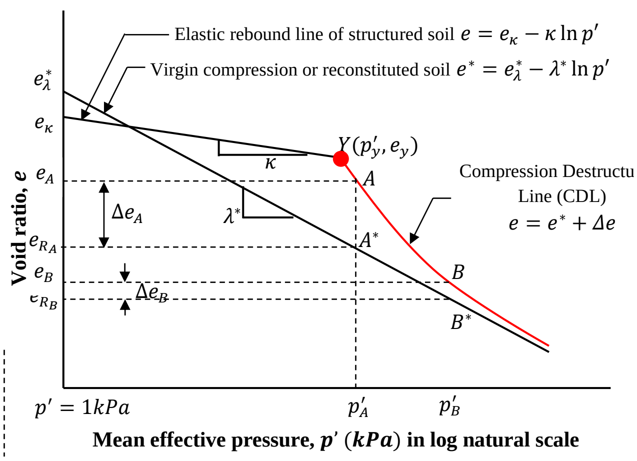


Figure 1 Idealization of compression behavior of natural soil

The structured void ratio, Δe is assumed to be a power curve with a form of $y = Ax^b$ (where A and b are constant terms) in $\Delta e - p'$ space. Power term b is always negative due to the nature of the curve for a positive value of A. Therefore, to yield a positive exponent term the curve can be expressed as follows:

$$\Delta e = A(p')^{-b} = A\frac{1}{(p')^b} \tag{2}$$

Here b is termed as *compression destructuring index* characterises the breakability of the soil structure and dimensionless parameter A is the *additional void ratio at unit pressure* ($p' = 1kPa$) represents the magnitude of the original soil structure. Influence of these parameters on soil destructuring is explained briefly in Liu et al. (2015) which is out of the scope of this paper. Liu et al. (2015) did not suggested any method beside trial and error to find out these parameters. Author suggests it for further reading.

For reconstituted soils, it is widely recognized that there is a linear relationship between the voids ratio e^* and p' in $e - \ln p'$ space as below

$$e^* = e_\lambda^* - \lambda^* \ln p' \tag{3}$$

Where e_λ^* is the void ratio at unit pressure ($p' = 1kPa$) and $\lambda^*$is the gradient of reconstituted virgin compression line in $e - \ln p'$ space. And thus the equation for a compression destructuring line (CDL) for a conventional isotropic compression test can be obtained by combining equation (2) and (3) into equation (1) as

$$e = e_\lambda^* - \lambda^* \ln(p') + A\frac{1}{(p')^b} \tag{4}$$

In case of one-dimensional virgin compression, p' is approximately linearly proportional to the effective vertical stress, σ_v' (Wroth, 1984) and thus equation (2) becomes

$$\Delta e = A\frac{1}{(K\sigma_v')^b} = A_{1D}\frac{1}{(\sigma_v')^b} \tag{5}$$

Similar to equation (4) the equation of CDL for one-dimensional compression test can be expressed as follows:

$$e = e_{\lambda-1D}^* - \lambda^* \ln(\sigma_v') + A_{1D}\frac{1}{(\sigma_v')^b} \tag{6}$$

3. PROPOSED METHODS TO FIND THE CDL PARAMETERS

To find the value for CDL parameters (i.e., A and b) from the experimental compression data two approaches (i.e., graphical and analytical) have been proposed. Both of the proposed approaches have been discussed in the following sections.

3.1 Graphical Approach

By taking logarithm on both sides, equation (2) becomes

$$\log(\Delta e) = \log\left(A\frac{1}{(p')^b}\right) = \log A - b\log(p') \tag{7}$$

Comparing equation (7) with straight line equation (i.e., $y = c + mx$) it is clearly seen that b and $\log A$ are nothing but the slope and intercept (i.e., $c = \log A$ and $m = -b$) of the straight line in $\log(\Delta e) - \log(p')$ space. On this basic geometrical concept a simple graphical approach to determine A and b is suggested by the author as follows:

(1) Structured void ratio Δe is measured at every experimental virgin compression data point (i.e., .$\Delta e = e - e^*$)

(2) $\Delta e - p'$are plotted on bi-logarithmic graph paper (log scale on both axes).

(3) A best fit straight line is drawn. The slope gives the value of compression destructuring index b. The intercept gives the additional unit pressure structured void ratio A for the corresponding b.

For one-dimensional compression test, the aforementioned process is similar only the vertical effective stress is used instead of mean effective pressure. The graphical approach explained here is a curve fitting method which can easily be incorporated into any spreadsheet program and the CDL parameters can be measured accordingly.

3.2 Two Reference Point Approach

Equation (2) can be rearranged to get an expression for parameter A as follows:

$$A = \Delta e(p')^b \tag{8}$$

At any reference point $A(p_A', e_A)$, structured void ratio Δe becomes Δe_A and thus equation (8) becomes

$$A = \Delta e_A(p_A')^b \tag{9}$$

Equation (2) can be rewritten for any reference point $A(p_A', e_A)$ as follows:

$$\Delta e = \Delta e_A(p_A')^b\frac{1}{(p')^b} = \Delta e_A\left(\frac{p_A'}{p'}\right)^b \tag{10}$$

By taking natural logarithm on both sides and rearranging equation (10) an expression for parameter b can be obtained as

$$b = \frac{\ln\left(\frac{\Delta e}{\Delta e_A}\right)}{\ln\left(\frac{p_A'}{p'}\right)} \tag{11}$$

For another reference point $B(p_B', e_B)$ equation (11) can be rewritten as

$$b = \frac{\ln\left(\frac{\Delta e_B}{\Delta e_A}\right)}{\ln\left(\frac{p_A'}{p_B'}\right)} \tag{12}$$

The approach to find the CDL parameters (i.e., A and b) by using two reference point can be summarized as follows:

(1) Firstly any two point $A(p_A', e_A)$ and $B(p_B', e_B)$ is identified on the experimental virgin compression line of natural soil and corresponding points $A^*(p_A', e_A^*)$ and $B'(p_B', e_B^*)$ on intrinsic compression line of reconstituted soil.

(2) Δe_A (i.e., $e_A - e_A^*$) and Δe_B (i.e., $e_B - e_B^*$) is calculated.

(3) Compression destructuring index, b is then calculated using equation (12).

(4) Additional unit pressure structured void ratio A is then obtained using equation (9).

The above-mentioned process is simple compared to the graphical approach.

For one-dimensional compression test, the vertical effective stress is used instead of mean effective pressure.

4. PROPOSED METHOD TO LOCATE YIELD POINT

According to the idealization of soil compression behavior shown in Figure 1, the yield pressure is the solution of elastic rebound line equation and the virgin compression curve equation since by definition both equations intersect each other at yield point (p_y', e_y). At yield point, the elastic rebound line equation can be written as

$$e_y = e_\kappa - \kappa \ln(p_y') \tag{13}$$

Where e_κ is the void ratio at unit pressure ($p' = 1kPa$) and κ is the gradient of elastic compression line in $e - \ln p'$ space.

The intrinsic normal compression line equation of the same soil in its reconstituted state (i.e., equation (3)) and equation of virgin compression destructuring line (i.e., equation (4)) at yield point (p_y', e_y) become as follows

$$e_y^* = e_\lambda^* - \lambda^* \ln(p_y') \tag{14}$$

$$e_y = e_\lambda^* - \lambda^* \ln(p_y') + A \frac{1}{(p_y')^b} \tag{15}$$

Equating equation (13) and (15) one can obtain the following equation as below

$$(e_\lambda^* - e_\kappa)(p_y')^b - (\lambda^* - \kappa)\ln(p_y')\,(p_y')^b + A = 0 \tag{16}$$

Any numerical method (e.g., Bisection method, iteration method, etc.) can be used to find out the value of p_y' by solving equation (16). After finding p_y', equation (13) or (15) can be used to solve for $e_y$and thus $Y(p_y', e_y)$ can be located on the $e - \ln p'$ space. This process can be summarized as follows

(1) Intrinsic soil parameters (e_λ^* *and* λ^*) of reconstituted normal compression line of same soil are measured from the experimental data.
(2) Soil parameters (e_κ *and* κ) for elastic rebound line of structured soil is measured from the experimental data.
(3) Virgin compression destructuring line parameters are obtained by any of the two methods proposed by the author.
(4) Iteration method is used to find out p_y' by solving equation (16).
(5) After finding p_y', equation (13) or (15) can be used to get e_y and thus Yield Point $Y(p_y', e_y)$ can be located.

5. PREDICTING THE COMPRESSION BEHAVIOR OF STRUCTURED SOIL

Published one-dimensional compression behavior of fifteen different soil samples in their natural and reconstituted state was collected from different papers over the past seven decades and studied. Soil parameters for reconstituted virgin compression behavior (i.e, λ^* and $e_{\lambda-1D}^*$) and elastic part of the natural soil (i.e, κ and $e_{\kappa-1D}$) are estimated first. After that the graphical approach and two reference point approach have been followed to measure the compression destructuring line (CDL) parameters (i.e, b and A) and their corresponding yield points $Y(\sigma_{vy}', e_y)$ have been located.

One-dimensional compression behaviors of aforesaid soils are presented in Figures 2. Effective vertical stresses, σ_v' are plotted in x axis and void ratios, e are shown in y axis. The experimental compression data of natural soil are represented by hollow squares. Hollow circles have been used to represent the experimental data of reconstituted soil. Reconstituted normal compression line modeled by equation (3) is shown by dotted line. Broken line represents the elastic part of the natural soil. Single solid line is the CDL simulation when graphical approach is used to determine the CDL parameters which are used in the simulation. Simulation using two reference point approach to find CDL parameters is presented by double stroke solid line. Solid dots represent the corresponding yield points. Values of these soil compression parameters are tabulated in Table 1.

Microsoft Excel has been used to identify the CDL parameters using both the approaches. The experimental Δe at different mean effective stresses/effective vertical stresses are the only inputs inserted in two different columns. In case of two reference point approach, a universal process has been taken to select the two point $A(p_A', e_A)$ and $B(p_B', e_B)$ for all soil samples. First point $A(p_A', e_A)$ is approximately the starting point of the CDL, where Δe is the maximum and the point $B(p_B', e_B)$ is the furthest point possible from point A where structure breakdown is almost complete (i.e., Δe is minimum).

6. DISCUSSIONS

CDL parameters obtained from both the approaches can simulate the compression behaviors with some variations. Graphical approach successfully fits the compression behavior data for most of the soil samples illustrated in Figure 2 except Mexico City Clay and Pisa Clay showed in Figure 2(a) and 2(i) respectively.

For two reference point approach an early start of destructing is clearly visible in Figure 2 (k), (l), (n) and (o) for Jangyu, Lingyungang, Gulf of Guinea and Bangkok clay respectively shifting the whole CDL to the left of the experimental data. On the other, late start can be seen in case of predicting the compression behavior of Ebarg Clay shown in Figure 2(f).

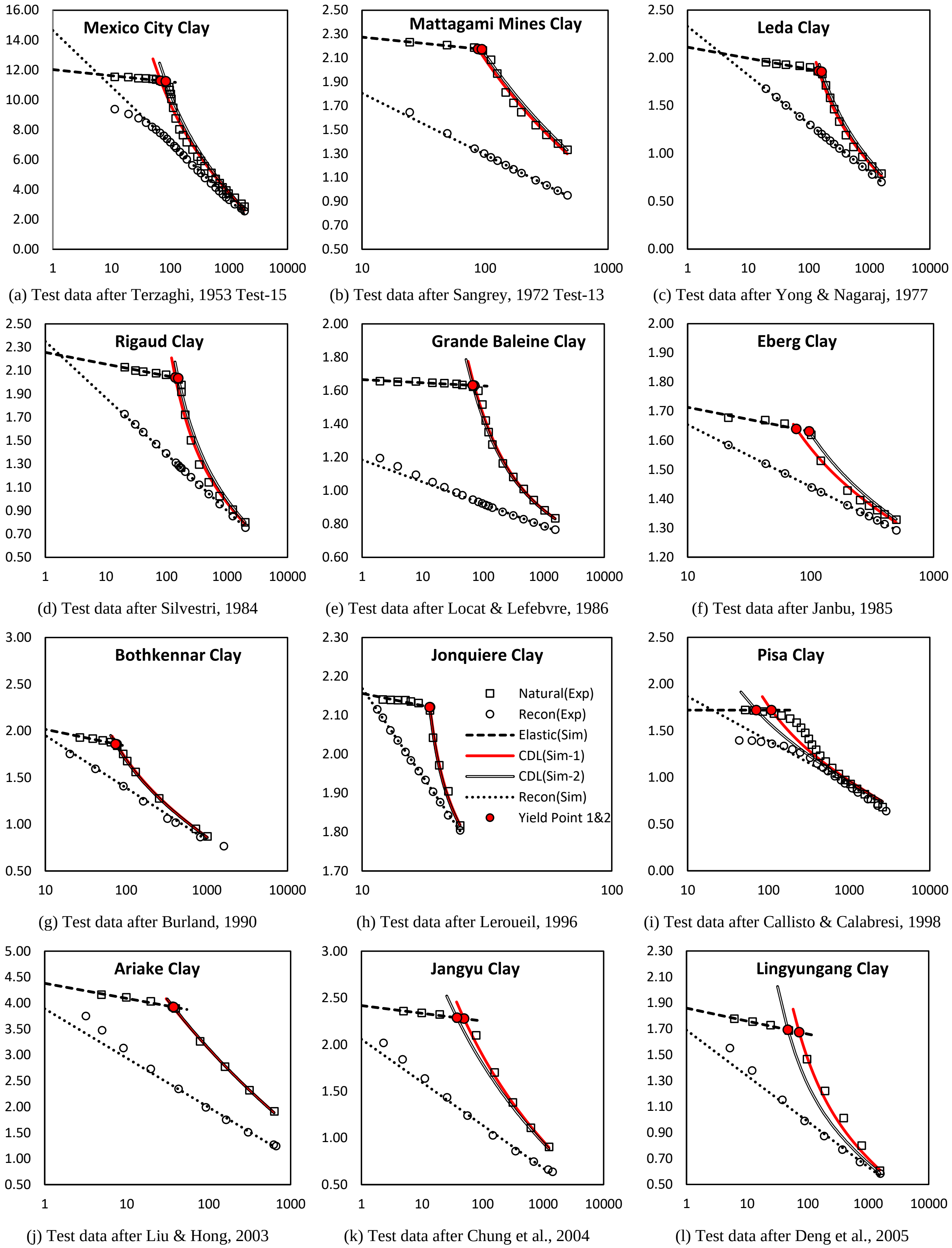
Although two reference point approach failed to predict the compression behavior for some cases, it can be used for quick estimation of CDL parameters initially for a trial and error process since it also gives a good approximation. Besides, both of the processes failed to predict the complex compression behavior of Pisa clay as shown in Figure 2(i) by missing the top half portion of the CDL.

A notable phenomenon arises during the simulation of Jonquiere clay. It is clearly perceived that there is a sudden breakdown of soil structure within a small range of effective vertical stress increment. Both approaches yield extraordinarily high values of A (1.02E+11 and 6.32E+11 for graphical and two reference point approach respectively) presented in Table 1.This is due to the steep nature (approximately vertical nature) of the compression curve.

7. EFFECT OF REFERENCE POINTS SELECTION ON CDL PARAMETERS

Theoretically, CDL parameters should be the same for any sets of two reference points since equation (12) is a general expression and must remain constant for all pair of points on the CDL. But due to the uncertainty of test compression data precision, CDL parameter may vary. To investigate the effect of reference point selection study was made on Mexico City Clay and presented in line graphs in Figure 3. First reference point $A(\sigma_{vA}', e_A)$ was taken close to yield pressure point and varied (i.e., initialization of destructuring). The second point $B(\sigma_{vB}', e_B)$ was taken were the destructuring is almost complete and varied. Figure 3(a) and (b) shows the variation of CDL parameters b and A respectively. From Figure 3, it can be clearly seen that the variation is rather arbitrary in nature due to the inaccuracy of the experimental data. In Figure 3 (a) parameter b varied from a maximum value of 0.99 to a minimum of 0.73 with an average value of 0.88 considering all the values of b. The value of parameter b for Mexico City Clay was found to be 0.822 previously while taking the furthest two points as point of reference.

Similarly, Figure 3 (b) also represents the random variation of parameter A with respect to the selection of two reference points. This random variation of b and A are similar in nature since parameter A depends on parameter b and varied accordingly. In Figure 3 (a) parameter A varied within the range of 78.77 to 339.86 with an average of 193.55 for which was previously found to be 145.70 as shown in Table 1. For this particular clay the graphical approach suggests the value of $b = 0.802$ and $A = 105.37$. Hence, it can be deduced that theoretically two reference point approach is correct but it depends on the accuracy of the compression data.



(a) Test data after Terzaghi, 1953 Test-15

(b) Test data after Sangrey, 1972 Test-13

(c) Test data after Yong & Nagaraj, 1977

(d) Test data after Silvestri, 1984

(e) Test data after Locat & Lefebvre, 1986

(f) Test data after Janbu, 1985

(g) Test data after Burland, 1990

(h) Test data after Leroueil, 1996

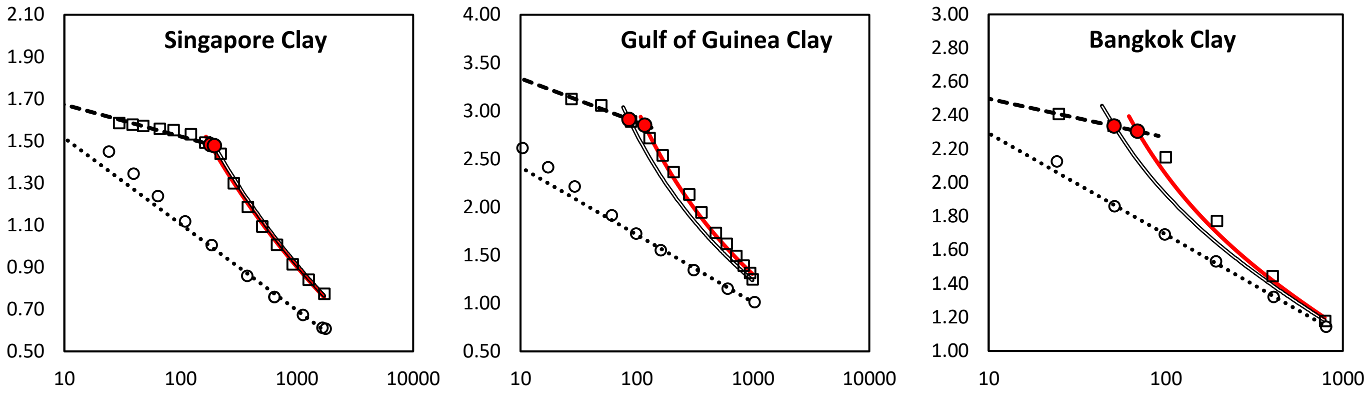
(i) Test data after Callisto & Calabresi, 1998

(j) Test data after Liu & Hong, 2003

(k) Test data after Chung et al., 2004

(l) Test data after Deng et al., 2005

Figure 2 One-dimensional compression behavior (e vs $\log(\sigma_v')$ curve) of some natural clays (cont.)

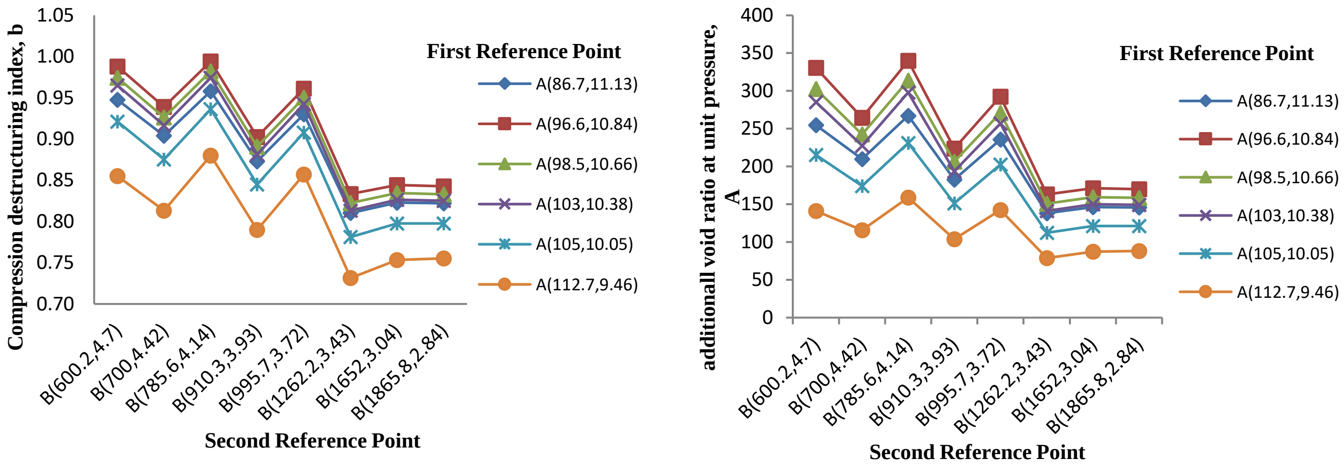


(m) Test data after Low el al., 2008 (n) Test data after Hattab et al., 2013 (o) Test data after Lorenzo & Bergado, 2004

Figure 2 One-dimensional compression behavior ($\boldsymbol{e}$ **vs** $\mathbf{log}(\boldsymbol{\sigma}'_{\boldsymbol{v}})$ curve) of some natural clays

Table 1 Values of soil compression parameters

Soil Sample	λ^*	$e^*_{\lambda-1D}$	κ	$e_{\kappa-1D}$	**Graphical Approach**				**Two Reference Point Approach**							
					b	A	σ'_{vy}	e_y	σ'_{vA}	e_A	σ'_{vB}	e_B	b	A	σ'_{vy}	e_y
Mexico City Clay	1.63	14.65	0.18	12.03	0.802	105.37	68.74	11.28	86.67	11.13	1865.83	2.84	0.822	145.70	83.68	11.24
Mattagami Mines Clay	0.22	2.32	0.05	2.38	0.535	9.35	87.71	2.18	96.34	2.16	469.41	1.33	0.514	8.97	94.16	2.17
Leda Clay	0.22	2.33	0.05	2.11	0.982	85.06	146.97	1.86	169.46	1.83	1607.91	0.79	0.881	58.51	164.04	1.86
Rigaud Clay	0.21	2.35	0.04	2.26	1.216	296.91	140.18	2.04	159.18	2.02	2013.54	0.80	1.110	204.54	157.11	2.04
Grande Baleine Clay	0.06	1.18	0.01	1.67	0.739	16.16	71.17	1.63	68.51	1.62	1558.56	0.83	0.737	15.24	67.03	1.63
Eberg Clay	0.09	1.87	0.04	1.80	1.025	14.83	76.67	1.64	101.83	1.62	501.19	1.33	0.999	18.14	97.41	1.63
Bothkennar Clay	0.24	2.51	0.08	2.20	0.949	24.74	76.63	1.86	77.87	1.84	1023.80	0.87	0.982	27.11	73.89	1.86
Jonquiere Clay	0.41	3.11	0.06	2.29	9.197	1.02E+11	18.71	2.12	18.70	2.11	24.73	1.82	9.835	6.32E+11	18.62	2.12
Pisa Clay	0.21	2.34	0.00	1.72	0.895	23.11	109.27	1.72	51.94	1.72	2611.57	0.68	0.762	6.65	71.11	1.72
Ariake Clay	0.41	3.89	0.13	4.38	0.294	4.36	36.31	3.93	39.72	3.89	633.70	1.91	0.301	4.54	37.29	3.92
Jangyu Clay	0.20	2.06	0.04	2.42	0.410	4.94	49.39	2.28	40.09	2.28	1262.19	0.90	0.384	3.86	37.89	2.29
Lingyungang Clay	0.15	1.69	0.04	1.86	0.865	26.02	72.70	1.67	49.30	1.69	1579.44	0.60	0.968	24.74	47.23	1.69
Singapore Clay	0.18	1.92	0.07	1.82	0.499	6.45	180.81	1.48	221.22	1.44	1728.82	0.77	0.503	6.99	195.08	1.48
Gulf of Guinea Clay	0.31	3.12	0.20	3.79	0.659	296.91	116.82	2.85	89.70	2.89	995.83	1.25	0.668	22.49	85.62	2.91
Bangkok Clay	0.26	2.90	0.10	2.73	0.994	34.89	69.22	2.31	50.84	2.34	796.91	1.18	0.995	23.49	51.11	2.34



(a) Variation of compression destructuring index, b (b) Variation of additional void ratio at unit pressure, A

Figure 3 Variation of CDL parameter based on the selection of two reference points for Mexico City Clay
(Test data after Terzaghi, 1953 Test-15)

8. CONCLUSIONS

In this paper, a theoretical background to model the virgin compression behavior of structured soil on the basis of polynomial curve equation (power function) has been reviewed based on the destructuring framework proposed by Liu et al. (2015). Two methods (i.e., graphical and analytical method named here as two reference point approach) have been proposed by the author to estimate the compression destructuring line (CDL) parameters. Also, rational approach to find the yield pressure has been proposed. The compression data for fifteen different soils published in various research papers in their natural and reconstituted state have been used to confirm the proposed procedures to compute CDL parameters.

The author recommends to use the graphical approach in all practical cases since it fitted the best and based on considering all the experimental data points which neutralize the inaccuracies. It is also mentioned to use two reference point approach for rapid estimation of CDL parameters since it depends on the selection of reference points. The systematic approach to locate the yield pressure point is also found very useful to work with. The methods presented in this paper eradicate the laborious process of trial and error and other conventional processes for finding CDL parameters and to locate the point of yielding. All these methods are systematic and can be easily incorporated into computer programs.

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