

A Framework for the Destructuring of Clays during Compression

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ABSTRACT: Based on the work by Liu and Carter (1999, 2000), a framework for the compression behaviour of structured clays is proposed, in which two entities of an existing soil are differentiated and described clearly: the original structure of the soil and the destructuring the soil has experienced. A theoretical Compression Destructuring Line (CDL) is proposed to describe the whole destructuring process of soil from its original or un-destructured state. Soils of the same original structure form a unique CDL, irrespective of loading history or structuring/destructuring history. The “theoretical” original structure of a soil is represented by parameters A and c , which are detectable from compression tests on soil specimens with or without destructuring. The destructuring a soil has experienced is dependent on its current yielding stress and is quantified when the value of the yield stress is determined. The compression behaviour of four types of clay with twenty-two tests is then analysed. It is seen that the compression behaviour of clays with various structures is described well, and the magnitude of destructuring can be quantified by the proposed method.

Keywords: Clays, Compression, Destructuring, Structure of soils.

1. INTRODUCTION

Soil is made up of particles. The arrangement and bonding of the soil particles is defined as soil structure. The soil structure is an important factor for its mechanical behaviour. In the current geotechnical engineering practice, a soil particularly a clay in laboratory reconstituted state is assumed to possess no structure and the difference between an existing soil state and its corresponding reconstituted state is generally referred to as the structure of the soil (e.g., Burland 1990; Gens and Nova, 1993; Liu et al, 2011). It has long been observed that both the compression behaviour and shearing behaviour of soil may vary remarkably with soil structure (e.g., Casagrande, 1932; Skempton and Northey, 1952; Cotecchia and Chandler, 1997; Leroueil, 2001; and Amorosi and Rampello, 2007; and Horpibulsuk et al., 2007). The structure of soil found in situ is usually formed during their depositional history. In contrast, laboratory specimen is often dependent on sample preparation method and the introduction of new materials can significantly change the structure of the parent clay. The removal of soil structure is referred to as destructuring, and loading frequently leads to destructuring (e.g., Leroueil and Vaughan, 1990; Schmertmann, 1991; Horpibulsuk et al, 2005; and Masin et al, 2006).

In recent years, there have been numerous studies in which a theoretical framework for describing the behaviour of structured soils has been formulated (e.g., Whittle, 1993; Liu et al, 2003; Baudet and Stallebrass, 2004; Yan and Li, 2011; Suebsuk et al, 2015). Based on a study of the virgin compression behaviour of structured soils, Liu and Carter (1999, 2000) proposed a simple equation to describe the compression behaviour of structured clays, mainly for the structure formed in situ. It has been seen that the study of the compression behaviour reveals useful information on the destructuring of soil and can be employed as a basis for understanding mechanical properties of structured soils under general loading (e.g., Horpibulsuk et al, 2010; and Suebsuk et al., 2010, 2011, 2015). In this article, the work by Liu and Carter (1999, and 2000) is revisited and extended. A framework for the destructuring of clay is thus proposed. In the new framework, two basic entities for a structured soil are differentiated and described separately. They are the original structure of the soil, and the destructuring the soil has experienced. Finally, the compression behaviour of soils is analysed with various structured such as naturally structured, lime treated, cemented, and chemical treated. General discussion on destructuring of soils is also conducted.

Following the suggestion of Burland (1990), the properties of a reconstituted soil are called the intrinsic properties, and are denoted by the symbol $*$ attached to the relevant symbols. For the situations where reinforcement materials such as cement or chemicals are added, the standard reconstituted behaviour of the parent clay without added materials is used as reference behaviour to measure the influence of “soil structure”. Consequently, the influence of soil structure is measured as the difference in the mechanical response between a treated soil and the parent soil. This assumption of reference state behaviour is made for simplicity. It has the advantage of predicting the behaviour of soil with various cement contents without the requirement of tests on the soil with individual added materials in reconstituted states, providing that model parameters for cementation structure are properly determined.

2. A FRAMEWORK FOR THE DESTRUCTURING OF CLAY

Based on the work by Liu and Carter (1999 and 2000), the compression behaviour of structured clay is idealised as shown in Figure 1.

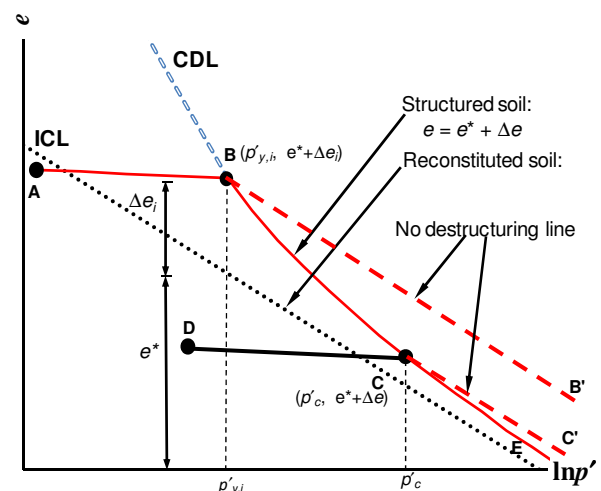


Figure 1 Destructuring of clay during compression

In this figure, p' is the mean effective stress, e represents the voids ratio for a structured soil, e^* is the voids ratio for the corresponding reconstituted soil at the same stress state during virgin yielding, Δe , the additional voids ratio, is the difference in voids ratio between a structured soil and its corresponding reconstituted soil. Hence, the virgin compression behaviour of a structured soil can be expressed as

$$e = e^* + \Delta e \quad (1)$$

The additional voids ratio Δe varies during virgin yielding as

$$\Delta e = \Delta e_i \left(\frac{p'_{y,i}}{p'} \right)^b \quad \text{for } p' \geq p'_{y,i} \quad (2)$$

Δe_i is the additional voids ratio at $p' = p'_{y,i}$, where virgin yielding begins (Figure 1). b is the compression destructuring index. From experimental observation, it is found that for soils with strong structure such as stiff clay or artificially cemented clay, the additional voids ratio does not approach zero with the increase of compression stress (e.g., Cotecchia and Chandler, 1997; Horpibulsuk et al, 2004; Kamaruzzaman et al, 2009; Consoli et al, 2012). Thus, equation (2) is modified as

$$\Delta e = (\Delta e_i - c) \left(\frac{p'_{y,i}}{p'} \right)^b + c \quad \text{for } p' \geq p'_{y,i} \quad (3)$$

Parameter c is the part of the additional voids ratio that cannot be removed by compression loading. It is given by

$$c = \lim_{p' \rightarrow \infty} \Delta e \quad (4)$$

Based on the above work, a destructuring framework is proposed for the compression behaviour of structured clays. The main reference of the compression behavior of a structured clay is a theoretical Compressional Destructuring Line (CDL). CDL, in the $e - p'$ space, is obtained by rewriting equation (3) in terms of the “original” structure of the soil and a stress state entity p' as follows and

$$e = e^* + \frac{(A - c)}{(p')^b} + c \quad (5)$$

In the equation, A is a dimensionless parameter to quantify the magnitude of soil structure. Comparing Equations (1) and (5), it can be seen that A is numerically equal to the additional voids ratio at $p' = 1$ kPa. This is a mathematical coincidence because A is a constant and the additional voids ratio varies monotonically from infinitive to zero.

CDL is proposed to describe the whole destructuring process of soil from its original or un-destructured state. The “theoretical” original structure of a soil is represented by parameters A and c because their values are independent of the stress quantities and thus are not affected by destructuring process. Soils of the same original structure form a unique CDL, irrespective of loading history or structuring/destructuring history. The destructuring framework includes the following characteristics (Figure 1).

- (1) Soil stays on CDL when it is in virgin yielding state, i.e., the current stress is the yielding stress. CDL forms the boundary of soil states in the $e - p'$ space.
- (2) Soil behaviour is divided into two regions by the current yielding stress: pure elastic behaviour and virgin yielding behaviour.
- (3) When the current stress state is less than the yielding stress, soil stays inside CDL and soil behaves purely elastically.

- (4) Destructuring occurs during virgin yielding and there is no destructuring during pure elastic deformation.
- (5) Elastic compression index κ may vary with soil structure.

CDL, is plotted in Figure 1, the valid range for the equation is $0 < p' < \infty$. Destructuring takes place progressively with virgin yielding. Two observations can be made. (a) Soil on different states of the same CDL possesses different structures. This is because destructuring takes place for loading from a state with less mean effective stress to the other state. (b) Although soil on different states of the same CDL possesses different structures, the structures of all the states of the same CDL originate from the same structure, but experiences different magnitudes of destructuring.

As shown in Figure 1, suppose a soil with an initial yielding stress $p'_{y,i}$, soil behaves purely elastic until stress state B with the yielding point with $p'_B = p'_{y,i}$. The initial structural yielding stress can be formed by the initial soil structure or by the destructuring or loading to this value. Virgin yielding occurs for continuing loading. If there is no destructuring, then $\Delta e = \text{constant}$. The virgin compression of the structured is parallel to the ICL*, i.e., line BB' as shown in Figure 1. Because of the removal of soil structure, the additional voids ratio sustained by soil structure decreases, the compression line follows line BCE. Soil behaves elastic for unloading at C, and exhibits virgin yielding if the current stress exceeds the historical maximum stress p'_C . The “virgin compression line” at point C is CC' if there is no destructuring.

Following the theory of Modified Cam Clay model, the isotropic compression line for reconstituted clay (ICL*) is given by

$$e^* = e^*_{IC} - \lambda^* \ln p' \quad (6)$$

where e^*_{IC} and λ^* are two soil parameters for ICL*. The compression behaviour of structured clay can be written in terms of the current yielding stress p'_y and the current stress p' as follows:

$$e = e^*_{IC} - (\lambda^* - \kappa) \ln p'_y - \kappa \ln p' + \frac{(A - c)}{(p'_y)^b} + c \quad (7)$$

If the current stress p' is less than the yielding stress $p' < p'_y$, soil behaves elastically. If the current stress p' is equal to the yielding stress $p' = p'_y$, virgin yielding occurs for continuing loading and the soil state is on CDL. Parametric studies are made to illustrate some features of the destructuring of clays, and they are shown in Figures 2 to 4. The values of equation parameters used for simulation are listed in Table 1, except those are specifically selected for the investigation. Because only virgin yielding behaviour is demonstrated here, there is no need to identify the value of κ .

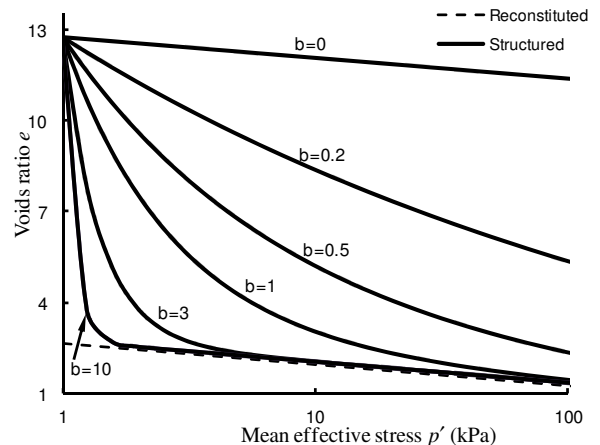


Figure 2 Influence of parameter b on destructuring

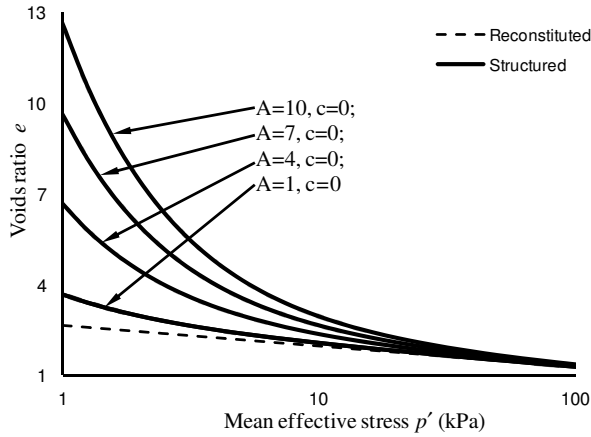


Figure 3 Influence of parameter A on destructuring

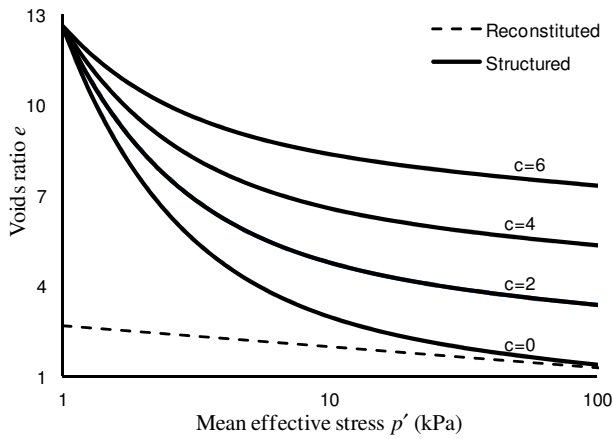


Figure 4 Influence of parameter c on destructuring

Table 1 Values of equation parameters

Parameter	e^*_{I-D}	λ^*	A	b	c
Value	2.65	0.3	10	1	0

- (1) Destructuring takes place progressively with virgin yielding. Two extremities are seen here. (a) If the soil has no structure or in reconstituted states, $\Delta e = 0$. (2) If the soil undergoes no structuring, $\Delta e = \text{constant}$. For this situation, $b = 0$ or $c = A$.
- (2) The influence of parameter b : b is the destructuring index, representing the breakability of the soil structure. As seen in Figure 2, the rate of reduction in the breakable additional voids ratio increases with the value of the compression destructuring index, *i.e.*, the more rapid the destructuring, the higher the value of b . The valid range for b is $0 \leq b < \infty$. For soft clay, usually $b \geq 1$. There is no enough data for an accurate identification of parameter b , $b = 1$ is assumed for soft clay.
- (3) The influence of parameter A: As seen in Figure 3, parameter A represents the magnitude of the original soil structure. The greater the original soil structure, the higher the value of A. A is a constant for a given structured soil. However, it should be noted that the structure of a given soil varies with yielding because of destructuring. The value of A is equal to the additional voids ratio at $p' = 1$ kPa.
- (4) The influence of parameter c: As seen in Figure 4 as well as equation (4), parameter c represents the part of cementation structure that cannot be removed by compression loading.

- (5) The current yielding stress p'_y is an indication of the magnitude of destructuring the soil has experienced. The higher the value of p'_y , the larger the amount of soil structure that has been removed, the closer the ICL to the ICL*.

3. THE FRAMEWORK FOR ONE DIMENSIONAL COMPRESSION

For one dimensional compression, usually the vertical effective stress σ'_v is measured and employed directly for describing soil behaviour in the $e - \ln \sigma'_v$ space. Consequently, the Compression Destructuring Line (CDL) for one dimensional compression is written as

$$e = e^* + \frac{(A - c)}{(\sigma'_{v,y})^b} + c \quad (8)$$

For a given type of soil structure, it is assumed that the compression destructuring index b and c will take the same value in equations (3) and (4).

The compression behaviour of structured clay can be written in terms of the current yielding stress $\sigma'_{v,y}$ and the current stress σ'_v as follows:

$$e = e^*_{I-D} - (\lambda^* - \kappa) \ln \sigma'_{v,y} - \kappa \ln \sigma'_v + \frac{(A - c)}{(\sigma'_{v,y})^b} + c \quad (9)$$

where e^*_{I-D} is the voids ratio for virgin compression of a reconstituted soil at $\sigma'_v = 1$ kPa. Parameter λ^* , κ , A, c, and b are assumed to be the same as those for isotropic compression. If the current stress σ'_v is less than the yielding stress $\sigma'_v < \sigma'_{v,y}$, soil behaves elastically. If the current stress is equal to the yielding stress $\sigma'_v = \sigma'_{v,y}$, virgin yielding occurs for continuing loading and the soil state is on CDL.

4. ANALYSIS OF EXPERIMENTAL DATA

The compression behaviour of four clays with various structures are simulated and investigated by using the proposed framework. They are the naturally structured stiff Pappadai clay (Cotecchia and Chandler, 1997), the lime treated soft Louiseville clay (Locat et al, 1996), the bentonite contaminated with sulfate (Sridharan et al, 1990), and the cement treated Bangkok clay (Lorenzo and Bergado, 2004). For cemented Bangkok clays, specimens are made with four different initial water contents and three different cement contents. The water contents are $w = 100\%$, $w = 130\%$, $w = 160\%$, and $w = 200\%$. The cement contents are 5%, 10%, and 15%.

The values of soil parameters are listed in Table 2. Comparison of simulations and experimental data are plotted in Figures 5 to 10. The tests are one dimensional compression tests, and thus equation (9) is employed for simulations. The values of all parameters are determined directly from experimental data except parameters e^*_{I-D} and λ^* for bentonite contaminated by sulphate. The values for these two parameters are estimated based on the trend of the behaviour of the naturally structured soil. As seen in equation (9), soil behaviour within the current yielding stress is elastic. Individual unloading and reloading line can be determined when the corresponding yielding stress is identified. It is seen that overall the proposed destructuring framework provides quantitative description of compression behaviour of clays with good accuracy over a wide range of applied stress and for various soil structures.

The following features of the influence of soil structure on the mechanical properties of soil are observed.

- (1) Strictly speaking, the elastic compression index κ^* is dependent on soil structure, particularly the bonding effect. In the case of cement treated soil, it is clearly that κ^* decreases with cement amount.

Table 2 Values of equation parameters

Fig.No	Soil	Reference	e^*_{1-D}	λ^*	A	b	c	κ	$\sigma'_{v,y}$ (kPa)
Fig. 5	Stiff Pappadai clay Natural	Cotecchia et al., 1997	1.85	0.154	200	0.9	0.035	0.022	2700, 5600, 30000
Fig. 6	Soft Louiseville clay Lime content 2% 5% 10%	Locat et al., 1996	4.1	0.55	6.8 14.5 26	0.38 0.38 0.38	0 0 0	0.1 0.1 0.1	0.43 3.6 20.5
Fig. 7	Benonite Natural Sulfate contaminated	Sridharan et al., 1990	3.35	0.36	43 305	1 1	0 0.15	0.12 0.12	29 92.5
Figs 8, 9, 10.	Bangkok clay Parent clay Natural 5% cement $w = 200\%$ $w = 160\%$ $w = 130\%$ $w = 100\%$ 10% cement $w = 200\%$ $w = 160\%$ $w = 130\%$ $w = 100\%$ 15% cement $w = 200\%$ $w = 160\%$ $w = 130\%$ $w = 100\%$	Lorenzo et al., 2004	3.13	0.3	40 48 48 48 48 120 120 120 120 120 148 148 148 148	1 0.65 0.65 0.65 0.65 0.65 0.65 0.65 0.65 0.65 0.65 0.65 0.65 0.65	0 0.1 0.1 0.1 0.1 0.15 0.15 0.15 0.15 0.15 0.2 0.2 0.2 0.2	0.07 0.04 0.04 0.04 0.04 0.01 0.01 0.01 0.01 0.01 0.007 0.007 0.007 0.007	82, 1600 74.7 118 190 405 278 477 728 1120 442 750 935 1510

- (2) The value of c is not zero in some cases. In this situation, the behaviour of the structured soil is not asymptotic to that for the parent soil in reconstituted states.
- (3) The destructuring index b is a relatively stable parameter. For a given parent clay, its value can be assumed to be dependent mainly on the mechanical constraints imposed during the formation of the structure. It is seen that b maintains the same value for cemented Bangkok clay prepared by the same method but with different cement contents and water contents. Similarly the value of b is the same for lime treated Louiseville clay. However, it should be noted this assumption may be used for estimation only when a reliable identification of parameter b is not available.

Parameter A is useful to quantify the magnitude of soil structure. For Pappadai clay, the value of A is the same for the naturally structured clay at different depths, but the value of $\sigma'_{v,y}$, indicating the yielding stress associated with soil structure, increases with depth (Figure 5). For Bangkok clay, the value of A is the same for the treated clay with the same cement content but at different water contents, but $\sigma'_{v,y}$ decreases with water content (Figures 8, 9, 10). Therefore, CDL is the theoretical destructuring line starting from unstressed state where there is theoretically "original" (equation 5), meanwhile the current yielding stress represents the level of destructuring the soil has experienced (equation 7). In other words, for soils of the same CDL the structure corresponding to a greater value of $\sigma'_{v,y}$ can be obtained by removing its structure (here virgin yielding) from a structure with less value of yielding stress $\sigma'_{v,y}$.

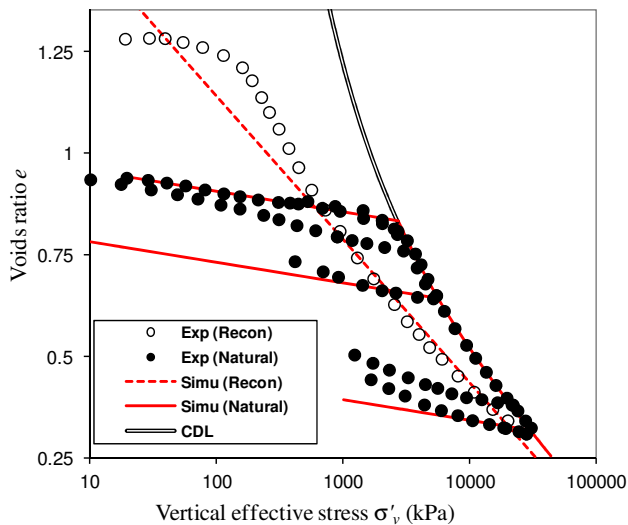


Figure 5 Compression behaviour of Pappadai clay
(Data after Cotecchia and Chandler, 1997)

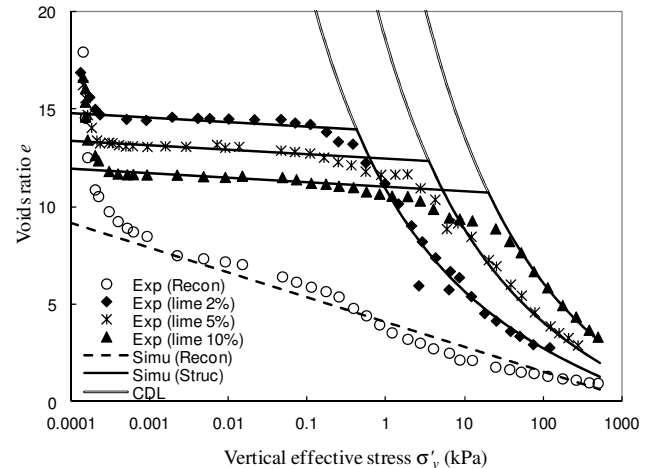


Figure 6 Compression behaviour of lime treated soft clay
(Data after Locat et al, 1996)

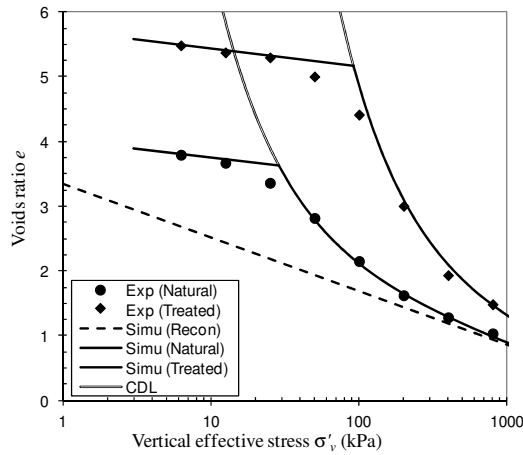


Figure 7 Compression behaviour of bentonite contaminated with sulfate (Data after Sridharan et al., 1990)

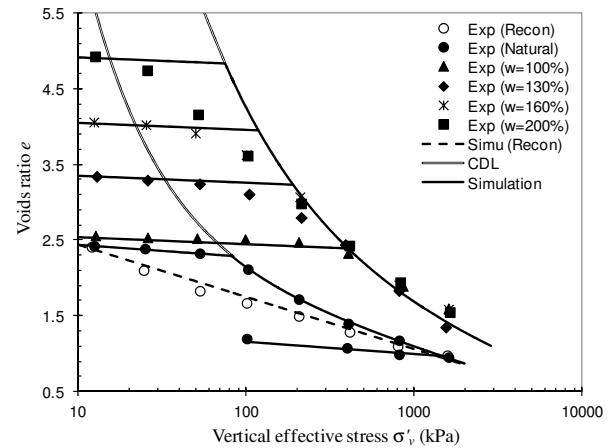


Figure 9 Compression behaviour of Bangkok clay with 10% cement (Data after Lorenzo and Bergado, 2004)

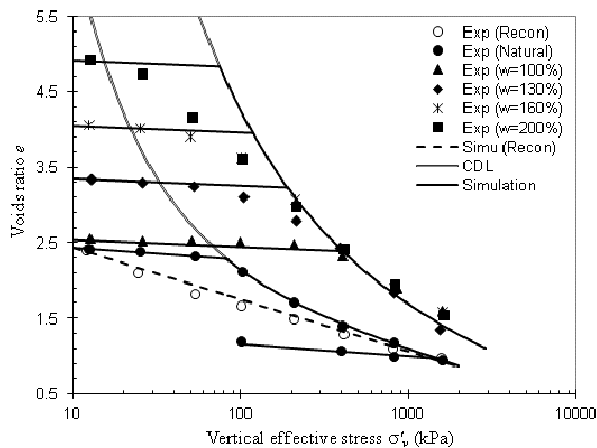


Figure 8 Compression behaviour of Bangkok clay with 5% cement (Data after Lorenzo and Bergado, 2004)

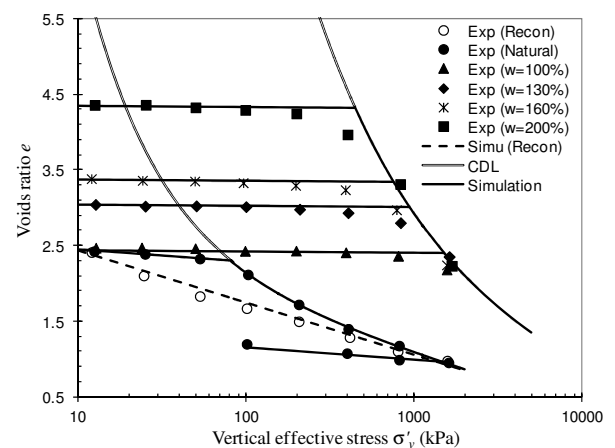


Figure 10 Compression behaviour of Bangkok clay with 15% cement (Data after Lorenzo and Bergado, 2004)

5. CONCLUSIONS

Based on the work by Liu and Carter (1999, 2000), a new framework for the destructuring of clay during compression is proposed. Two entities of an existing soil are differentiated and described clearly: the original structure of the soil by parameters A and c , and the destructuring the soil has experienced which is dependent on the current yielding stress. A theoretical Compression Destructuring Line (CDL) is proposed to describe the whole destructuring process of soil during compression from its original or un-destructured state. Soils of the same original structure form a unique CDL, irrespective of loading history or structuring / destructuring history. In this framework, the destructuring of a soil at any stage is represented by the yielding stress of the soil at that stage. The greater the yielding stress, the higher the destructuring the soil has experienced.

The compression behaviour of four types of clay with twenty-two tests is then analysed. The structures cover that of naturally structured stiff clay, lime treated soft clay, contaminated clay, and artificially cemented clay. The range of the stress varies from 0.0002 kPa to 30,000 kPa. It is seen that the compression behaviour of all these clays is well described by the destructuring framework, and the magnitude of desctructuring can be quantified by the proposed method.

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