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Compressibility of lightweight cemented clays

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ABSTRACT

Compressibility characteristics of a lightweight cemented clay are important issues for deformation analysis. This paper attempts to analyze and assess the compressibility characteristics of lightweight cemented clays. Three types of clay, kaolin, Bangkok clay and bentonite, representative of non- to high swelling clays are used for this study. It is found that a lightweight cemented clay is stable in the meta-stable state. The void ratio of a lightweight cemented clay is the sum of the void ratio sustained by the intrinsic soil fabric (destructured void ratio) and the additional void ratio due to cementation. At post yield state, the additional void ratio is made of two parts, the part that is inversely proportional to effective vertical stress and the residual additional void ratio, e_{sr}, which cannot be eliminated by the increase in effective vertical stress. The e_{sr} is mainly dependent upon the mineralogy or soil type (swelling potential). The suggested e_{sr} values are approximately 0.49 for kaolin, 0.18 for Bangkok clay and 0.10 for bentonite. The rate of destructuring, b is mainly dependent upon the soil structure (degree of cementation and fabric reflected by the initial void ratio and swelling potential). The relationships between e_{sr} versus liquid limit void ratio e_L and between b versus yield stress, initial void ratio and e_L are proposed. Based on the two proposed relationships, a practical (simple and rational) method for assessing the compressibility of lightweight cemented clay with various soil structures is suggested. The prediction method is useful not only for the quick determination of a compression curve with acceptable error, but also for the examination of the test results.

1. Introduction

When infrastructures such as road embankments and bridge foundations are constructed on soft soil deposits, several geotechnical engineering problems are encountered. These deposits tend to consolidate and undergo large vertical settlement and lateral deformation during and after construction due to incumbent loads. The problems are moreover related to short-term and long-term stability when an unexpected loading (e.g. earthquake) is imposed on the structures and soft ground system.

To solve these problems, the use of lightweight cemented clays with moderate to high strength as a backfill material to reduce the weight of the structure on the soft clay is an effective alternative means. Lightweight materials have wide applications in infrastructure rehabilitation and in the construction of new facilities. The lightweight cemented clay has been extensively used for highway and port construction in many countries such as Japan and Thailand (Satoh et al., 2001; Tsuchida et al., 2001; Hayashi et al., 2002; Otani et al., 2002; Jamnongpipatkul et al., 2009; Kikuchi and Nagatome, 2010 and Kikuchi et al., 2011). Most of the available researches focused on the compressive strength and durability while the study on the compressibility characteristics especially with constitutive equations useful for engineering computation is very limited. Compressibility characteristics of the lightweight cemented clay are important issues for deformation analysis.

It is now widely accepted in geotechnical engineering that the soil structure controls the mechanical behavior of clay. The term "soil structure" is determined by both the particle associations and arrangements (fabric) and cementation bond (Terzaghi, 1953; Mitchell, 1996; Miura et al., 2001 and Liu et al., 2011). Fabric is reflected by the void ratio and swelling potential of clay while the level of cementation bond is by cement content. Generally, the void ratio of cemented clay is higher than that of remolded clay of the same mineralogy. A material idealization of the compression behavior of cemented clay is shown in Fig. 1. The compression strain is low (about 0.05) up to the yield stress, σ'_y, due to the contribution of structure (Horpibulsuk et al., 2012b). Beyond the yield stress, there is sudden compression of relative high magnitude, which is indicated by the steep slope and attributed to the destructuring. When the cemented clay undergoes destructuring, the additional void ratio due to soil structure, e_s decreases. As the vertical

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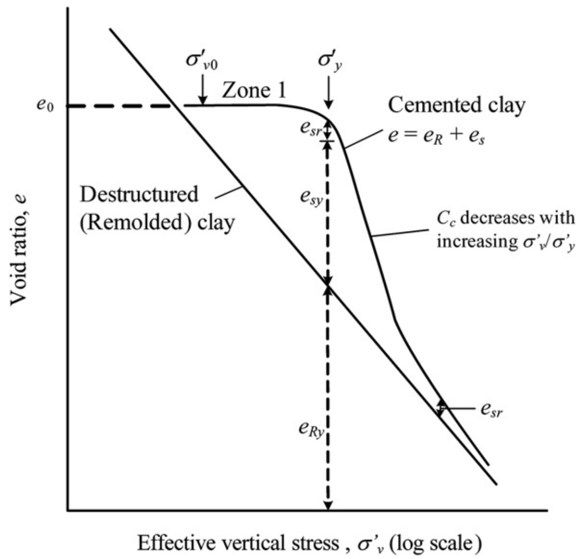

Fig. 1. Compression behavior of the structured clays.
Modified from Nagaraj et al. (1990) and Liu and Carter (1999).

effective stress, σ'_v increases, the compression curves corresponding to the cemented clay appear to be asymptotic to the curve for the destructured (completely remolded) clay. The influence of the soil structure tends to diminish as σ'_v increases. Progressive destructuring accompanies the plastic yielding (irrecoverable deformation) that is associated with the virgin compression (Nagaraj et al., 1998; Liu and Carter, 1999; Nagaraj and Miura, 2001; and Horpibulsuk et al., 2007). The void ratio at a particular effective vertical stress can be expressed as follows.

$$e = e_R + e_s \tag{1}$$

where e represents the void ratio for a cemented clay, e_R is the void ratio for the corresponding destructured clay and e_s is the additional void ratio attributed to soil structure. e_R is the void ratio supported by the intrinsic soil fabric of a destructured (completely remolded) sample.

Liu and Carter (1999 and 2000) analyzed compression behavior of over 20 different natural structured clays and found that the additional void ratio due to soil structure, e_s, in virgin yielding state is inversely proportional to $(\sigma'_v)^b$, where b is the destructuring index, quantifying the rate of destructuring. The additional void ratio is expressed in the form:

$$e_s = e_{sy}\left(\frac{\sigma'_y}{\sigma'_v}\right)^b + e_{sr} \tag{2}$$

where e_{sy} is the additional void ratio corresponding to the yield stress and e_{sr} is the residual additional void ratio sustained by soil structure that cannot be eliminated by an increase in effective vertical stress (when σ'_v approaches infinity, $e_s = e_{sr}$). Because the soil structure remains even at very high effective vertical stress beyond yield (Horpibulsuk et al., 2004b), e_{sr} is never null. e_{sy} is determined by considering that when $\sigma'_v = \sigma'_y$:

$$e_{sy} + e_{sr} = e_y - e_{Ry} \tag{3}$$

where e_y and e_{Ry} are the void ratios of cemented and destructured curves corresponding to the yield stress, respectively.

Parameter b represents the rate of reduction of the additional void ratio with loading. The rate of the removal of soil structure increases with the magnitude of b (i.e. the faster the destructuring, the higher the b value). The b value can be determined by the rate of the change in void ratio over the change in effective vertical stress with the consideration of the power relationship as described in Eq. (2). The b value can also be determined by fitting because the values of all the other parameters can be determined based on their physical meanings. A detailed parametric study on parameter b can be found in a paper by Liu and Carter (2000). The b value mainly depends on the type of soil structure, which is clay fabric (water content and clay type) and cementation bond. Generally, $b \geq 1$ for natural soft clay with high water content and low to moderate shear strength (high sensitivity) (Liu and Carter, 2000). Horpibulsuk et al. (2007) showed that for soft natural Bangkok clay, the b value is 1.0 and the e_{sr} value is 0.2, regardless of the sample disturbance (rate of destructuring) and the initial water content. The destructuring framework has been incorporated in many constitutive models such as Structured Cam Clay and Modified Structured Cam Clay models (Liu and Carter, 2002, 2003; Horpibulsuk et al., 2010; Suebsuk et al., 2010, 2011) for deformation analysis.

Nagaraj and Srinivasa Murthy (1986) analyzed compression lines of different destructured (remolded) clays. They revealed that the compression lines can be normalized by the liquid limit void ratio e_L, and the normalized compression line is called Intrinsic State Line, *ISL* represented by Eq. (4)

$$\frac{e_R}{e_L} = 1.23 - 0.276 \log \sigma'_v \tag{4}$$

where e is the void ratio and σ'_v is the effective vertical pressure (kPa).

Based on the extensive data of 26 destructured clays compiled from the literature, Burland (1990) proposed an Intrinsic Compression Line (*ICL*) for assessing the in-situ state of natural clays. The *ICL* is expressed by Eq. (5):

$$I_v = 2.45 - 1.285x + 0.015x^3 \tag{5}$$

where $x = \log\sigma'_v$. The void index is defined as:

$$I_v = \frac{(e - e_{100})}{C_c} \tag{6}$$

where e_{100} is the void ratio corresponding to $\sigma'_v = 100$ kPa and C_c is the compression index. e_{100} and C_c can be approximated in terms of e_L using the following equations:

$$e_{100} = 0.190 + 0.679e_L - 0.089{e_L}^2 + 0.016{e_L}^3 \tag{7}$$

$$C_c = e_{100} - e_{1000} = 0.256e_L - 0.04. \tag{8}$$

Horpibulsuk et al. (2011c) revealed that the *ISL* proposed by Nagaraj and Srinivasa Murthy (1986) and the *ICL* by Burland (1990) are only applicable for non- to low-swelling clays but not for high swelling clays. They proposed a generalized intrinsic compression curve for all clay types (both non- and high-swelling) and for various conditions of pore water chemistry. The newly proposed parameter designated as modified void index, I'_v is defined as:

$$I'_v = \left(\frac{e - e_{50}}{e_{50} - e_{1000}}\right) \tag{9}$$

where e_{50} is the void ratio corresponding to $\sigma'_v = 50$ kPa. The generalized intrinsic compression curve, which is the relationship between I'_v and $\log\sigma'_v$, for 10 kPa $\leq \sigma'_v \leq$ 1280 kPa was presented in the form:

$$I'_v = 0.029(\log\sigma'_v)^3 - 0.112(\log\sigma'_v)^2 - 0.733(\log\sigma'_v) + 1.427. \tag{10}$$