Engineering Geology 214 (2016) 20–28

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

On the normalized behavior of naturally and artificially structured clays

Dongxing Wang, Ph.D.Associate Professor [a,*,1], Leena Korkiala-Tanttu [b]

[a] Key Laboratory of Geotechnical and Structural Engineering Safety of Hubei Province, School of Civil Engineering, Wuhan University, 8 Dong Hu South Road, Wuhan 430072, China
[b] Department of Civil and Environmental Engineering, Rakentajanaukio 4A, PO Box 12100, Aalto University, FI 00076 Espoo, Finland

ARTICLE INFO

Article history:
Received 13 September 2015
Received in revised form 11 September 2016
Accepted 18 September 2016
Available online 20 September 2016

Keywords:
Natural clay
Artificially structured clay
Compression
Normalization
Void index
Generalization

ABSTRACT

The influence of soil structure on the volume change behavior of clay soils has been often studied with reference to intrinsic properties and normalization of reconstituted clays. However, to date, there has been relatively little research conducted on the normalizing behavior of naturally and artificially structured clays. In this paper, the yielding modes and normalization, by introducing the void index, are clarified for the one-dimensional compression of natural Finnish clays. Based on 24 samples with different cement contents and curing times, two novel approaches are proposed to normalize the post-yielding range of artificially structured clays. Laboratory results show that approach I, i.e., linear extrapolation of the post-yielding line in a log-log graph, can normalize well the compression behavior of artificially structured clays. However, the normalized curves of the void index vs. the effective stress in the semi-log plot deviate from Burland's intrinsic compression line (ICL) at very high consolidation stresses. To address this issue, a novel formulation of the ICL is deduced from laboratory data for artificially structured clays. Approach II, i.e., redefinition of the constants of compressibility to modify the void index, results in closer convergence of the normalized compression curves. The normalized curves by the modified void index agree well with the proposed intrinsic compression line for artificially structured clays (SICL). Finally, the generalization of Burland's ICL can redefine the intrinsic formulations corresponding to different levels of the yielding stress by modifying the void index.

1. Introduction

The behavior of remolded clays can be used as a basic frame of reference for assessing the effect of the soil structure on the compressibility and strength of naturally sedimentary clays (Skempton and Northey, 1953; Nagaraj and Srinivasa Murthy, 1986; Burland, 1990; Cotecchia and Chandler, 2000; Hong et al., 2012). Burland (1990) introduced the concept of "intrinsic properties" to interpret the characteristics of reconstituted clays since they are inherent to the soil and independent of the natural state. This means that the property of reconstituted clay is independent of the soil structure because of the lost memory of the experienced geological history.

The normalizing parameter represented by Eq. (1) is defined as the void index I_v, closely linked with the compression index C_c in Eq. (2). When the data of 26 remolded clays from the literature were normalized by I_v, the unique intrinsic compression line (ICL) was derived by Burland (1990), as shown in Eq. (3). Note that the void index I_v correlates the compression curves of various reconstituted clays with the void ratio at liquid limit e_L from 0.6 to 4.5 (i.e., $\omega_L = 25\%$ to 160%).

$$I_v = \frac{e - e_{100}}{e_{100} - e_{1000}} \tag{1}$$

$$C_c = e_{100} - e_{1000} \tag{2}$$

$$I_v = 2.45 - 1.285\log\sigma_v' + 0.015(\log\sigma_v')^3 \tag{3}$$

where σ_v' is the vertical consolidation stress in kPa and e_{100} and e_{1000} are the void ratios at σ_v' of 100 kPa and 1000 kPa, respectively.

Further discussions have been conducted on the intrinsic properties of various clays following Burland (1990). Hong and Tsuchida (1999) stated that the compression curves of remolded Ariake clays can be normalized by the void index I_v, and most natural Ariake clays lie above the sedimentation compression line. Tremblay et al. (2001) introduced the void ratios e_{10} and e_{100}, corresponding to stresses of 10 kPa and 100 kPa, respectively, to modify Burland's void index for the normalization of very soft clayey materials. Based on a wide range of natural and pure clays, Cerato and Lutenegger (2004) concluded that the intrinsic parameter I_v may not be a true intrinsic soil property but is dependent on sample preparation. The conclusion has important implications for interpreting the scattering phenomenon of the I_v-$\log\sigma_v'$ curves of the reconstituted samples at water contents of 1.0–1.75 times the liquid

---

* Corresponding author.
E-mail addresses: dongxing-wang@whu.edu.cn (D. Wang), leena.korkiala-tanttu@aalto.fi (L. Korkiala-Tanttu).

[1] Formerly, Postdoctoral Researcher, Department of Civil Engineering, Rakentajanaukio 4A, Aalto University, FI-00076 Espoo, Finland.

http://dx.doi.org/10.1016/j.enggeo.2016.09.006
0013-7952/© 2016 Elsevier B.V. All rights reserved.

limit. Hong et al. (2010, 2012) performed many laboratory tests on natural and reconstituted clays with water contents of 0.7–2.0 times the liquid limit. They observed the well-normalized behavior of both natural and reconstituted clays to a unique compression line using Burland's void index. Horpibulsuk et al. (2011) proposed a novel definition of the void index by incorporating the void ratio e_{50} at a vertical stress of 50 kPa for satisfactorily normalizing various remolded clays subjected to different pore water chemistries. Liu et al. (2013) proposed a simple systematic tool on the concept of the void index to estimate the compression behavior of reconstituted clays over a wide range of stresses and water contents. Wang and Abriak (2015) considered that Burland's equations may not be suitable for all types of soil, and cement-treated reconstituted soils fit Burland's equations better than lime-treated soils do. However, the above studies focused principally on the normalizing behavior of reconstituted clayey materials. The normalization of both naturally and artificially structured clays is less well established, especially concerning artificially structured clays with high yielding stresses. The cement-solidified clays are herein designated as “artificially structured clays” because of the formation of the artificial cementation structure (Sorensen et al., 2007; Suebsuk et al., 2009; Suebsuk et al., 2010; Suebsuk et al., 2011; Wang and Abriak, 2015; Wang et al., 2015).

Following previous studies, the current study endeavors to contribute to the understanding of the normalization of naturally and artificially structured clays. The typical types of compression curves and yielding modes are first discussed on natural clays in an attempt to clarify the fundamental mechanism for the compression behavior of natural clays. Keeping this in mind, the normalization of the compression behavior is subsequently investigated. For artificially structured clays, the degradation mode of the artificial soil structure is analyzed on 24 solidified clays at different curing times and cement contents. Two innovative approaches are proposed to facilitate the normalization of the compression behavior, especially for artificially structured clays with a high consolidation yielding stress.

2. Materials and methods

To investigate the compression behavior during the time-dependent stress-strain evolution, one-dimensional oedometers were used to test natural clays and artificially structured clays. As shown in Table 1, four types of natural clays were adopted, Otaniemi clay, Perniö clay, Petikko clay and Elimäki clay. One or two samples were chosen for Perniö clay (after Mataić et al., 2016), Petikko clay and Elimäki clay, while three samples of Otaniemi clay were tested to highlight the observed difference between them. The detailed data are presented in Table 1, which provides the sampling depth, initial water content, bulk density, specific density, liquid limit, organic content, clay fraction and silt fraction. The experimental results proved that there is no sand fraction in the studied clays. For Otaniemi clay, samples 1 and 2 from similar sampling depths in a single sample core look very much alike. They are clearly different from sample 3, which shows a higher initial water content and liquid limit. For Perniö clay, the liquid limit is approximately 82%, which is lower than its initial water content of 107%. It is interesting to find that Petikko clay sample 2 shows physical properties similar to those of Perniö clay, such as the initial water content and liquid limit, but these samples were taken from different sampling sites at different depths. The Elimäki clay sample presents basic characteristics that are different from those of Perniö clay, even though these samples were taken from similar sampling depths. This is mainly due to the potential difference in clay mineralogy. Note that the basic test results shown in Table 1 are only from specific tested samples, which cannot represent the general property of clays from Otaniemi, Perniö, Petikko and Elimäki in Finland.

The oedometer tests were carried out on samples in a stainless steel ring with a cross-sectional area of 20 cm^2 and a height of 2 cm. Natural clay samples were sheared and installed as carefully as possible to avoid sample disturbance. During testing, the samples were laterally constrained and drained to both the top and bottom surfaces. The evolution of the pore pressure was not measured during the compression process, and tap water was used in this study. Each loading was imposed for 24 h when the settlement due to the previous load ceased. For natural clays, oedometer tests were performed up to maximal vertical stresses of 864 kPa, 1088 kPa, 1240 kPa, 1389 kPa, 1736 kPa and 2242 kPa.

The artificially structured clay samples were prepared by mixing manually remolded samples from natural Otaniemi clays with cement. The cement used in the present study is a special material named Nordkalk Terra TM KC50 produced in Nordkalk Company in Finland. The average initial water content of the remolded clays (no cement) was 75.2% for the four samples. The mixture with a certain cement content was directly filled in four oedometer rings, as mentioned above, in a very short time to prepare similar and undisturbed samples. The solidified clay samples were afterwards hermetically preserved in a double layer of plastic bags at room temperature (approximately 22 °C) for 1, 7, 14 and 28 days. The amount of cement, 1, 3, 5, 7, 9, 11 and 13%, was calculated by the dry weight of the clays. Different from the natural clays, maximum loadings of 2170–2242 kPa were imposed for the cement-solidified clay samples, and each loading lasted for 24 h to obtain the full compression curves.

3. Yielding modes and normalization of naturally structured clays

3.1. Typical types of compression curves

The inverse ‘S-shaped’ compression curves of many natural clays in the e versus $\log\sigma_v'$ scale can be represented by two straight lines in a plot of $\ln(1 + e)$ or $\log(1 + e)$ against $\log\sigma_v'$ (Butterfield, 1979; Onitsuka et al., 1995; Sridharan and Prakash, 1996). Hong et al. (2012) indicated that the S-shaped curves of e-$\log\sigma_v'$ can also be observed on reconstituted clays, similar to those of many natural clays. As shown in Fig. 1(a), the oedometer test data for natural Otaniemi, Petikko, Elimäki and Perniö clays are presented in the e-$\log\sigma_v'$ plot. For these clays, the inverse ‘S-shaped’ curve can be clearly observed, especially for Perniö and Petikko clays. The ‘S′ shape of the compression curves of Elimäki clay and Otaniemi clay sample 2 can be illustrated more clearly if the compression curves can be extended to a large consolidation stress. As expected, the corresponding compression curves can be well interpreted in Fig. 1(b) by two straight lines in the $\ln(1 + e)$ vs. $\log\sigma_v'$ scale. As a typical feature of soft, sensitive, structured clays, the ‘S-shaped’ curves have been reported by Janbu (1967), Hong et al. (2012) and Mataić et al. (2016).

Table 1
Basic characteristics of natural clays.

Clays	Depth (m)	Initial water content (%)	Specific density	Bulk density (kN/m^3)	Liquid limit (%)	Organic content (%)	Clay fraction (%)	Silt fraction (%)
Otaniemi 1	2.87–2.90	55	2.79	16.54	48.9	0.4	62.7	37.3
Otaniemi 2	2.84–2.87	59	2.79	16.51	50.8	0.5	64.2	35.8
Otaniemi 3	1.92–1.95	79	2.74	15.42	63	0.1	80.8	19.2
Perniö	6.23–6.26	107	2.70	14.23	82	1.2	75.5	24.5
Petikko 1	4.70–4.73	93.2	2.70	14.70	76	–	71.0	29.0
Petikko 2	1.70–1.73	109	2.70	14.12	82	–	78.9	21.1
Elimäki	6.20–6.23	69.6	2.70	16.51	60.8	–	67.8	32.2