CONSOLIDATION CHARACTERISTICS OF A SILTY CLAY: CONCERNING THE EFFECT OF SOIL DISTURBANCE

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Abstract. In this paper, undisturbed specimen of a silty clay constituting of Phu Bai formation (ambQ_2^{1-2} *pb*) was collected from boreholes in Hue city and surrounding areas. The soil, under both undisturbed and disturbed conditions, was then subjected to standard one-dimensional consolidation tests with 7 loading increments. It is shown from the experimental results that the time to the end of primary consolidation (EOP), determined by Log Time method (t_{LT}) and 3-t method (t_{3T}), decreases with the load increment and under the same vertical stress, the primary consolidation of disturbed silty clay finish at a shorter time than those of the undisturbed one. The coefficient of secondary consolidation (C_α) increases with the vertical stress and reaches the maximum values before decreasing. The obtained values of C_α = 0.005 - 0.020 suggest a relatively low secondary compressibility of the silty clay constituting of Phu Bai formation.

Keywords: silty clay, soil disturbance, time to EOP, coefficient of secondary consolidation

1 Introduction

As an important aspect in the field of soil mechanics, consolidation characteristics of clays under external load, both static and cyclic patterns, have been studied extensively for a long history. Consequently, the effects of different loading conditions such as loading duration, frequency, intensity and pattern on the consolidation characteristics of soils have been clarified [1]. In which, secondary consolidation due to re-arrangement of soil particle after the dissipation of pore water pressure shows more difficulty to observe and therefore, problems related to the magnitude and the rate of such a settlement component are still insufficiently understand [2], meanwhile the secondary compression is considered as a main factor leading to the difference in the compressibility of clayey soils induced by static and cyclic loading [1]. Recently, by using oedometer test under both standard consolidation and in shear box of the cyclic simple shear test apparatus, the differences in the consolidation characteristics have been clarified for undisturbed and disturbed clays at different Atterberger's limits with and without cyclic loading history [3,4].

Organosedimentary materials are considered as disabsentable components within Quaternary stratigraphy of delta-coastal plains through Vietnam. In Thua Thien Hue province, dark coloured and weak organosedimentary soils are named as Phu Bai formation (ambQ_2^{1-2}*pb*) with their specific characteristics including high organic content, low bearing capacity and shear resistance, high compressibility. Moreover, besides spreading nearly continuously, Phu Bai formation also has its own very changeable thickness and distributing depth. In Hue city and surrounding areas, the soils are stratified close to ground surface and therefore causing adverse effects on buildings' foundation stability, historical monuments' lifetime as well as reduced technical and the economic efficiencies of construction in the areas [5-8]. Obtaining undisturbed specimen of such soft soils is always challenge and even under the undisturbed condition, the initial soil structure and skeleton are commonly affected during the sampling. Therefore, an observation of the effect of the soil disturbance on the geotechnical properties in general and on the consolidation characteristics specifically is important for foundation design on soft ground.

Because of the most common component constituting of Phu Bai formation [5], the silty clay (hereinafter called as Phu Bai silty clay) is therefore used in this study. The soil was subjected to one-dimensional standard consolidation tests with 7 loading increments ranging from 0.125 kgf/cm^2 to 16.0 kgf/cm^2. The settlement was measured with 24 hour-period for each increment and based on which, consolidation characteristics including the time to the end of primary consolidation (EOP) determined by Log Time method and *3-t* method and then, the coefficient of secondary consolidation were observed for both undisturbed and disturbed specimens.

2 Experimental aspects

In order to prepare testing specimens, the Phu Bai silty clay was taken from 6 boreholes at two construction projects in Hue city and used for this study. Index properties of tested soil are shown in Table 1.

Table 1. Average index properties of tested samples

Property	Value	Property	Value
Grain content (%)		Liquid limit, w_L (%)	50.7[(a)]
Clay	20.5[(a)]	Plastic limit, w_P (%)	36.0[(a)]
Silt	62.5[(a)]	Plasticity index, I_p	14.7[(a)]
Sand	17.0[(a)]	Compression index C_c	0.49[(b)]
Specific gravity, G_s	2.708[(b)]	Organic content (%)	7.5[(a)]

[(a)] *The data was refered from [5] and checked with two experiments on the soil sample used in this study;*
[(b)] *the average values of three experiments on the soil sample used in this study.*

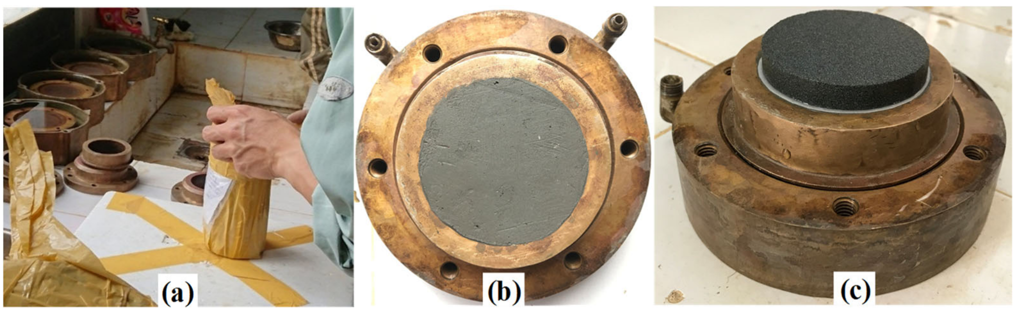

Fig. 1. Preparation of undisturbed specimen: (a) trimming specimen, (b) tested specimen in consolidation ring and (c) tested specimen in test box with filter paper and porous stone on the top.

Firstly, soil samples from boreholes were collected, transported and restored following Vietnamese Standard [9]. The sample was then trimmed and used for oedometer test (Fig. 1). In this study, the one-dimensional consolidation test was carried out under Japanese Standard (JIS A 1210) [10] and under this standard, 7 load increments ($\Delta\sigma'_v$) were applied (from σ'_v = 0.125 kgf/cm^2 to σ'_v = 16.0 kgf/cm^2) and the load increment ratio was set as unity ($\Delta\sigma'_v/\sigma'_v$ = 1) with the loading interval of 24 hours [10]. Situations of the consolidation test at different stages are shown in Fig. 2.

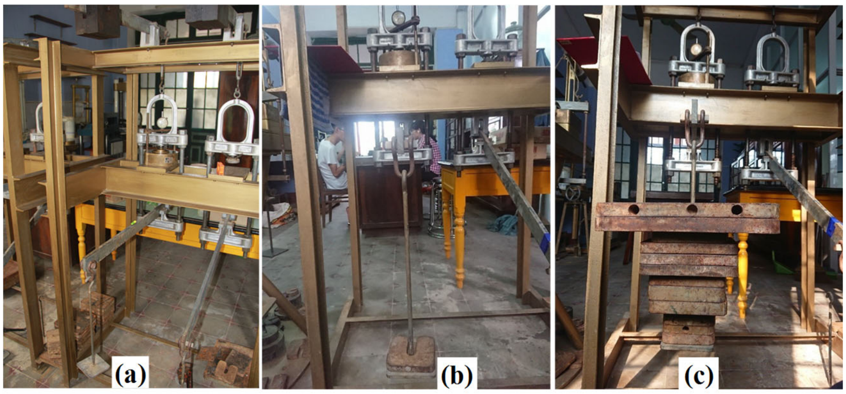

Fig. 2. Standard one-dimensional consolidation test at different stages: (a) Test box including soil specimen before loading, (b) first load increment and (c) final load increment

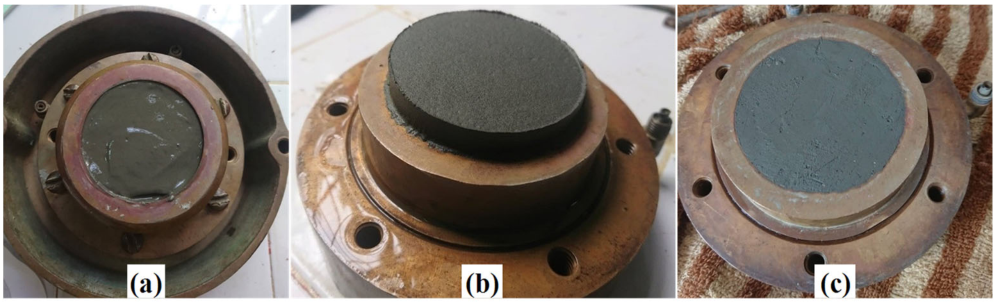

Fig. 3. Preparation of disturbed specimen: (a) pouring slurry into the double-specimen ring, (b) disturbed specimen after releasing from the final load increment of 0.25 kgf/cm^2 and (c) disturbed specimen in specimen ring before testing

In order to prepare disturbed specimen, disturbed soil was made directly from the undisturbed one by mixing with de-aired water to form slurry having water content of about 1.5×w_L. The slurry was kept for one day under the constant water content and was then poured into the double-specimen ring which was designed for preparing disturbed specimen (Fig. 3a). The slurry was then subjected to the load increments of $\Delta\sigma'_v$ = 0.03, 0.06, 0.125 and 0.25 kgf/cm^2 with the duration of 24 hours for each increment. Thereafter, soil specimen was released from the load (Fig. 3b) and then used for standard consolidation tests (Fig. 3c). Procedures and the performance of standard consolidation test on disturbed specimen are similar to those used for undisturbed one.

3 Results and discussions

3.1 Time to EOP of undisturbed and disturbed Phu Bai silty clay

Based on the settlement measurement with time, the vertical settlement in strain (ε_v, %) is plotted against elapsed time (t, minute) in Fig. 4 for undisturbed and disturbed Phu Bai silty clay subjected to different load increments. In order to clarifying the consolidation characteristics, undisturbed and disturbed specimens should be subjected to the same load increment as seen on the undisturbed specimen in Fig. 4. On the other hand, the fisrt load increment of the consolidation test should be smaller than the pre-consolidation pressure of soil specimen and therefore, the first load of σ'_v = 0.125 kgf/cm^2 should be applied to the disturbed one. The results indicate that the settlement increases with elapsed time regardless of the vertical stress and that, such a tendency is more unique on undisturbed specimen which shows slightly smaller total settlement after the final loading increment (16.0 kgf/cm^2).

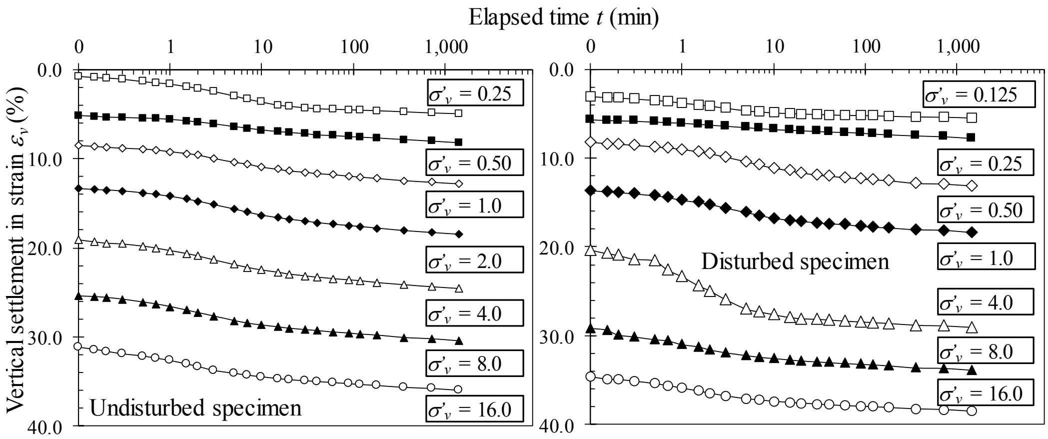

Fig. 4. Settlement-time relations of undisturbed and disturbed specimens under different load increments (Unit of the load increment is kgf/cm^2)

It is known that cementing materials originated during the sedimentation affect the properties of clayey soils and in nature, organic matter partly constitutes the representative cementing materials of the soil [1]. The compressibility of clays is therefore influenced by organic matter and the compression index (C_c) of organic clayey soils has been confirmed to be in proportional to the organic matter content [11]. Silty clay like the soil used in this study with high sand content usually shows relatively high permeability resulting in a relatively short time for pore water dissipation or to EOP. Meanwhile the settlements in Fig. 4 continue to increase within 24 hours suggesting that the time to EOP should be determined so that the secondary settlement could be observed for each load increment.

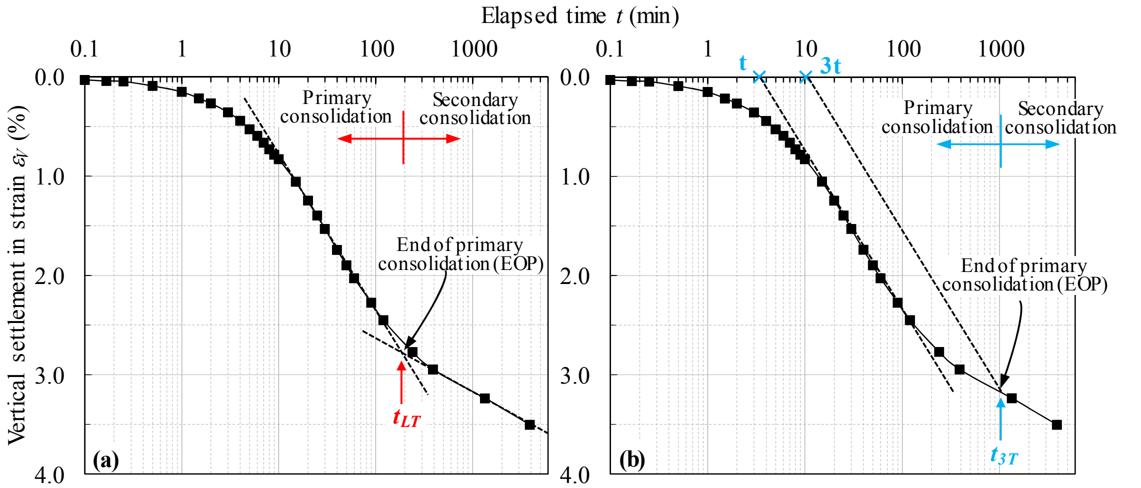

Fig. 5. Determination of the time to EOP by (a) Log Time method (t_{LT}) and (b) *3-t* method (t_{3T}) (Modified after Nhan et al. 2019 [3])

In order to estimate the time to EOP of the soil, the Log Time method [12] which is practically applied to estimate the settlement of clay layers and the *3-t* method which is commonly applied for laboratory investigation [10,13]. The detail of these two methods and typical applications on different clays have been shown in our previous research [3,14]. Obtained results of the time to EOP determined by using Log Time method (t_{LT}) are shown in Fig. 6 for undisturbed and disturbed Phu Bai silty clay. Despite of several scattering, the results indicate that t_{LT} generally decreases with the vertical stress and that, under the same load increment, undisturbed specimen shows larger value of t_{LT} than those on disturbed one. It is known that the rate of consolidation depend on the ability of water to flow through the soil matrix and with undisturbed condition, cohesion and the particle bond tend to prevent the movement of pore water reducing the consolidation rate compared with those of disturbed one.

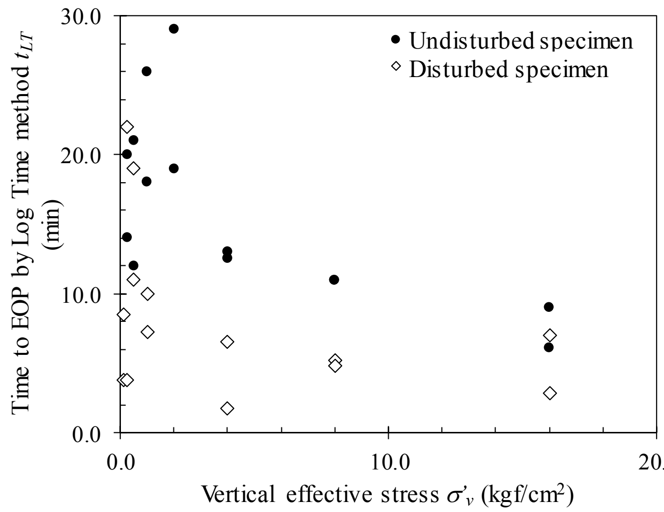

Fig. 6. Changes in t_{LT} with σ'_v for undisturbed and disturbed Phu Bai silty clay

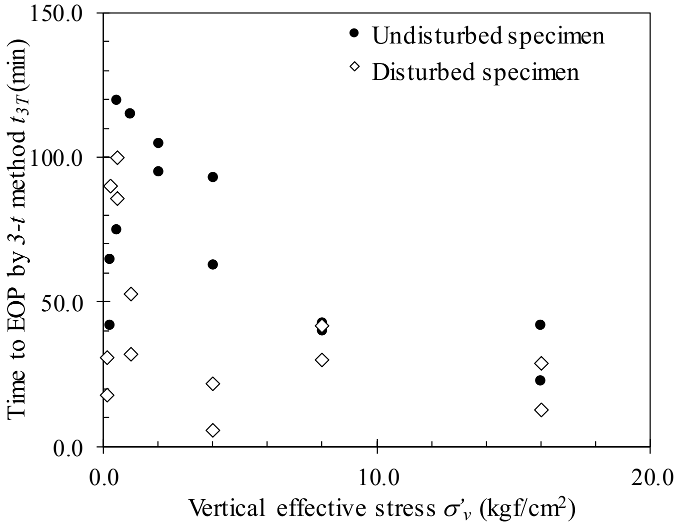

Fig. 7. Changes in t_{3T} with σ'_v for undisturbed and disturbed Phu Bai silty clay

Based on a comparison of t_{LT} with the time for completed dissipation of the pore water pressure which is a standard measurement of EOP, it is shown in the most cases that, t_{LT} is considerably smaller and in laboratory where the primary consolidation should be confirmed for next experiment, the *3-t* method is considered as an effective solution [13]. In Fig. 7, results of the time to EOP determined by *3-t* method (symbolized as t_{3T}) are shown for each load increment on undisturbed and disturbed specimens. Similar to the tendency in Fig. 6, t_{3T} decreases with σ'_v regardless of the disturbance of soil structure and that, undisturbed specimens show larger values of t_{3T} than those of the disturbed ones.

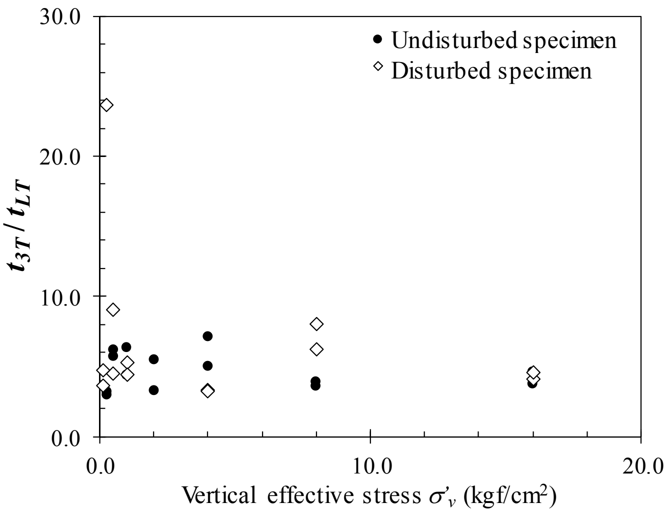

Fig. 8. Changes in the ratio of t_{3T} to t_{LT} (t_{3T}/t_{LT}) versus σ'_v

When comparing the results between Fig. 6 and Fig. 7, t_{3T} is evidently larger than t_{LT}, then the ratio of t_{3T} to t_{LT} (t_{3T}/t_{LT}) is plotted against σ'_v by symbol in Fig. 8. Despite of two scattering values (t_{3T}/t_{LT} = 9.1 and 23.7), for the silty clay used in this study, t_{3T} is at 3 to 7 times higher than t_{LT} for undisturbed specimen and from 3.3 to 8.1 times for the disturbed specimen.

3.2 Coefficient of secondary consolidation of Phu Bai silty clay

By measuring the settlement through the secondary consolidation, the coefficient of secondary consolidation in terms of void ratio (C_α) can be determined as schematically shown in Fig. 9. In this figure, C_α is the slope of the curve of the void ration (e) versus logarithm of time (t) after the primary consolidation and defined by Eq. (1) as followed:

$$C_\alpha = \frac{e_1 - e_2}{\log t_2 - \log t_1} \quad (1)$$

where e_1 and e_2 are the void ratio corresponding to time t_1 and t_2 in the secondary consolidation stage (Fig. 9).

Relationships between C_α and σ'_v are shown in Fig. 10 for undisturbed and disturbed Phu Bai silty clay. It is seen that C_α firstly increases with σ'_v and reaches the maximum values of about C_α = 0.013 and C_α = 0.020, corresponding to the vertical stress of about σ'_v = 1 - 2 kgf/cm^2 and σ'_v = 2 - 3 kgf/cm^2 for disturbed and undisturbed specimens, respectively. Secondly, C_α decreases to smaller values. The values of C_α = 0.005 - 0.020 suggest the low secondary compressibility of the silty clay constituting of Phu Bai formation.

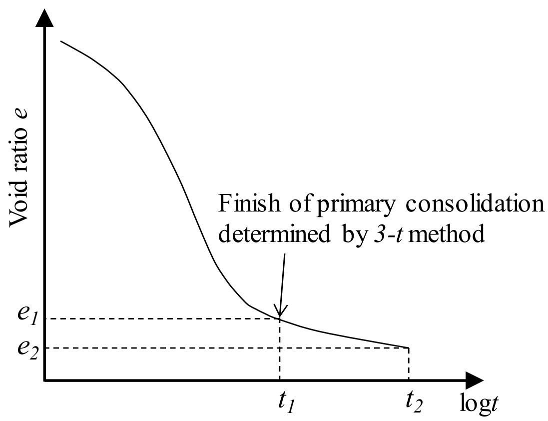

Fig. 9. Schematic illustration of the determination method of C_α

By carrying out a series of one-dimensional consolidation tests on an organic clay, Mesri [15] indicated that at small consolidation pressure, remolded specimens with a more dispersed fabric show smaller value of C_α compared with those of the undisturbed ones. However, C_α of remoulding specimens increases with σ'_v to a maximum value and then decreases and finally approaches to those of undisturbed specimens at high consolidation pressure. Meanwhile in Fig. 10, when $\sigma'_v \leq 1.0$ kgf/cm^2, the differences of C_α between undisturbed and disturbed specimens are unclear due to several scattering on the results. For higher consolidation stress, better results are obtained indicating the lower secondary compressibility of disturbed specimen than those of undisturbed one and such discrepancies seem to decrease with the increase in the vertical stress.

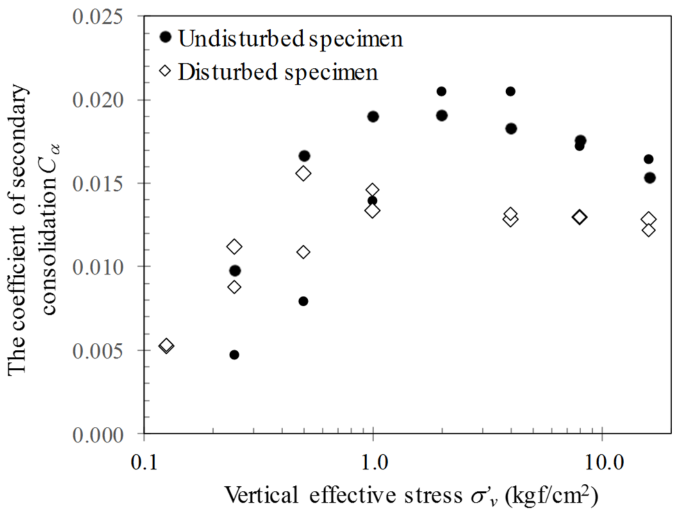

Fig. 10. Changes in C_α with σ'_v for undisturbed and disturbed Phu Bai silty clay

4 Conclusions

The main conclusions are as follows:

1. The silty clay constituting of Phu Bai formation (ambQ$_2^{1\text{-}2}$ *pb*) under undisturbed condition shows slightly smaller settlements than those of the disturbed one, meanwhile the time to EOP of the former condition is longer than those of the latter.

2. The time to EOP, determined by both *3-t* method (t_{3T}) and Log Time method (t_{LT}), decreases with the vertical stress regardless of the disturbance of soil structure. Ratio of t_{3T} to t_{LT} changes from $t_{3T}/t_{LT} = 3$ to $t_{3T}/t_{LT} = 7$ for undisturbed specimen and from $t_{3T}/t_{LT} = 3.3$ to $t_{3T}/t_{LT} = 8.1$ for the disturbed one.

3. The silty clay constituting of Phu Bai formation shows a relatively low secondary compressibility with the coefficient of secondary consolidation in terms of void ratio (C_α) is about $C_\alpha = 0.005 - 0.020$. In addition, the coefficient of secondary consolidation of the soil firstly increases with the vertical stress and reaches maximum values at $\sigma'_v = 1 - 2$ kgf/cm^2 and $\sigma'_v = 2 - 3$ kgf/cm^2 for disturbed and undisturbed specimens, respectively. Thereafter, C_α decreases as the vertical stress increases.

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References

1. Fujiwara, H., Ue, S., Yasuhara, K. Secondary compression of clay under repeated loading. Soils and Foundation, Vol. 27(2), page 21-30, Japan, 1987.
2. Yasuhara K. *A practical model for secondary compression*. Soils and Foundations, Vol 22(4), page 45-56, Japan, 1982.
3. Nhan, T. T., Nhat, P. C., Huong, H. T. S., Thach, T. X. Thien, D. Q., Nhan, N. T. T. *Time to the end of primary consolidation (EOP) of soft clayey soils: concerning the effect of Atterberg's limit and cyclic loading history*. Hue University Journal of Science: Techniques and Technology, Vol. 128(2A), page 29–41, Vietnam, 2019.
4. Nhan, T. T., Matsuda, H. *Pore water pressure accumulation and settlement of clays with a wide range of Atterberg's limits subjected to multi-directional cyclic shear*. Vietnam Journal of Earth Sciences, Vol. 42(1), page 93–104, Vietnam, 2020.
5. Nhan, N. T. T. *Study on the physico-mechanical properties of ambQIV 1-2 sedimentary soils in Thua Thien Hue coastal plain and proposal of the improvement solutions by using sand compaction pile method for civil structures*. Master thesis, University of Sciences - Hue University, 95 pages, Hue city, Vietnam, 2004.
6. Thao, P. T. *Study on soft soil profiles in Hue city and surrounding areas and proposal of the effective ground improvement solutions*. Master thesis, University of Sciences - Hue University, 86 pages, Hue city, Vietnam, 2004.
7. Vy, T. T. B. *Study on methods for Engineering geological mapping with large scale*. Master thesis, University of Sciences - Hue University, 76 pages, Hue city, Vietnam, 2007.
8. Tung, H. T. H. *Estimation of the bearing capacity of concrete pile upon diferent soil profiles in Hue city*. Master thesis, University of Sciences - Hue University, 65 pages, Hue city, Vietnam, 2007.
9. TCVN 2683:2012. *Soils - sampling, packing, transportation and curing of samples*, Ministry of Science and Technology, Vietnam, 10 pages, 2012.
10. JGS. *Soil test procedure and explanation*, Japanses Geotechnical Society, Japan, 251 pages, 2001.
11. Kamon, M. *The properties of engineering and stabilization on soft ground*. Doctoral Thesis, 176 pages, Japan, 1978.
12. Casagrande, A. *The determination of the pre-consolidation load and its practical significance*. Proceedings of the first international conference on soil mechanics, Vol. 3, page 60-64, Havard, 1936.
13. Germaine J. T., Germaine A. V. *Geotechnical laboratory measurements for engineers*, John Wiley & Sons, Inc., 351 pages, New Jersey, USA, 2009.
14. Nhan T. T. *Study on excess pore water pressure and post-cyclic settlement of normally consolidated clay subjected to uniform and irregular cyclic shears*. Doctoral dissertation, Yamaguchi University, 131 pages, Japan, 2013.
15. Mesri G., Godlewski P. M. *Time and stress-compressibility interrelationship*. Journal of the Geotechnical Engineering Division, ASCE, Vol. 103(GT), page 417-430, USA, 1977.