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Evaluation of structure of aged marine deposits by means of standard compression curves

L'évaluation de structure des dépôts marins âgés au moyen de la courbe de compression normale

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ABSTRACT: The concept of standard compression curves for marine clays are shown and the degree of structure of marine deposits is evaluated based on the concept, which consists of ultimate standard compression curve, USC, and standard compression curve from an initial void ratio, SCC(e_0). The values of in-situ specific volume index I_{sv0} of Osaka Bay Pleistocene Clay and Ariake clays are much larger than those determined by SCC (e_0). The high degree of the structures are due to aging effect during the sedimentation process for Osaka Pleistocene Clays, and due to the reduction of liquid limit due to the leaching effects for Ariake Clays.

RÉSUMÉ: Le concept des courbes standard de compactage pour les argiles marins sont montrés et le degré de structuredes dépôts marins est évalué a basé sur le concept, qui se compose de la courbe standard finale de compactage, USC, et de la courbe standard de compactage d'un premier taux vide, SCC(e_0). Les valeurs du volume spécifique in-situ classent I_{sv0} de l'argile pléistocène de compartiment d'Osaka et les argiles d'Ariake sont beaucoup plus grands que ceux déterminés par SCC (e_0).

1 INTRODUCTION

It is known that mechanical property of naturally sedimented clay is quite different from that of remolded clay, because natural clay has a structure due to secondary compression and/or cementation effects during sedimentation (Tavenas and Leroueil, 1977; Jamiolkowski et al.,1985; Burland,1990). However, the effects of the structure have been discussed only qualitatively and no practical method has been proposed to measure the effects quantitatively. Recently the authors have proposed a concept of standard compression curves (SCC) for marine clays to explain the various aspects of e-log p relationship of clays in a unified manner. This paper shows that the degree of structure of marine deposits can be evaluated easily based on the SCC concept.

2 STANDARD COMPRESSION CURVES OF MARINE CLAYS

2.1 *Ultimate standard compression curve (USC)*

The fundamental assumption of the standard compression curve is the existence of Ultimate Standard Compression Curve (USC). USC is described as follows (Tsuchida and Gomyo,1995; Tsuchida,2000);

a) When clay is consolidated one-dimensionally from slurry with large initial void ratio, it shows the linear relationship between ln f (=1+e) and log p. This curve is named Ultimate Standard Compression Curve (USC).
b) In case that a natural sedimentary clay has a structure due to aging, the clay can keep a void ratio e_0 larger than the value given by USC.
c) When clay is remolded with a small void ratio and is consolidated, the void ratio becomes smaller than the value given by USC. When a clay sample is consolidated after being disturbed, the void ratio becomes also smaller than the value given by USC.
d) By consolidating clay sample with the pressure larger than the consolidation yield stress p_c, the structure of clay due to aging is gradually broken and the effects of the remolding and the sample disturbance also gradually disappear. When the clay is consolidated at the stress level much larger than p_c, the e-log p compression curve converges into the USC.

Figure 1 illustrates the USC concept in the ln f - log p system. USC can be described as follows;

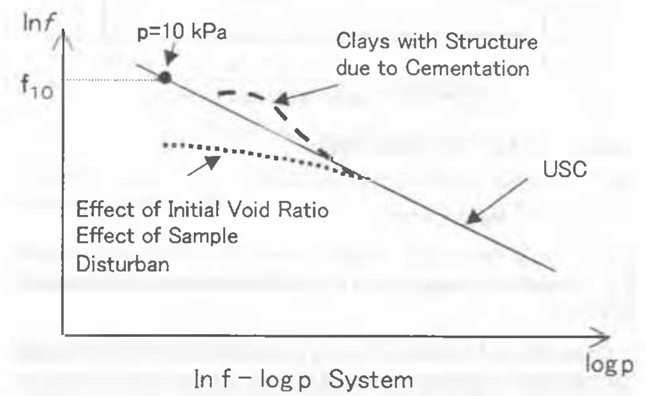

Figure 1. Ultimate standard compression curve, USC.

$$\ln f = -C(\log p - 1) + \ln f_{10} \tag{1}$$

where, f is specific volume and equal to void ratio e plus 1, f_{10} is the specific volume when p=10 kN/m^2 on USC. C is a gradient of USC which is given by the compression index C_c and e as $C = C_c/(1+e)$.

To study the validity of USC, 725 consolidation test data of 18 marine deposits including Japan, Thailand, Singapore, Indonesia and United Kingdom were analyzed by the following procedure:

1) To plot the specific volume f and the consolidation pressure p in ln f –log p system.
2) To ascertain the linearity between ln f and log p in the region of $p \geqq 2p_c$, and determine a straight line (USC) for ln f - log p relation. To calculate the compression ratio, C and f_{10}.

The obtained data of C and f_{10} are plotted against the specific volume at liquid limit, f_L in Figures 2 and 3, respectively. As shown in Figures2 and 3, the following equations are obtained by the regression analysis;

$$C = 0.27 \ln f_L \tag{2}$$

$$\ln f_{10} = 1.20 \ln f_L \tag{3}$$

Combining Equations (2) and (3) with Equation (1), the following equation can be obtained;

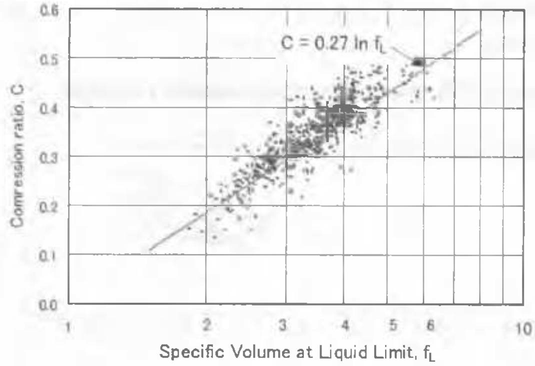

Figure 2. $C - \ln f_L$ relationship.

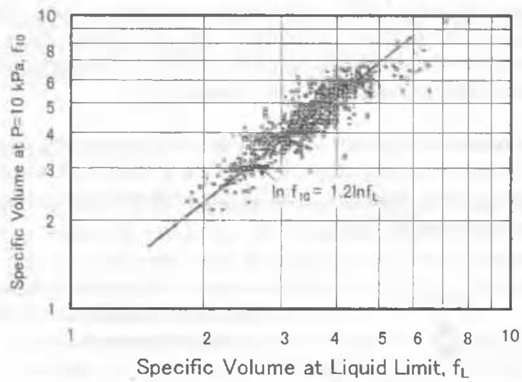

Figure 3. $\ln f_{10} - \ln f_L$ relationship.

$$I_{sv} = -0.27 \log p + 1.47 \quad (4)$$

2.2 *Standard Compression Curve from an initial void ratio SCC(e_0)*

Generally, when consolidation pressure p is not large enough, the void ratio e is smaller than USC due to the effect of low initial void ratio. The standard compression curve from an initial voids ratio, e_0, is called SCC(e_0) in this study. SCC(e_0) is the e-log p relationship, of which the consolidation starts at an initial void ratio e_0 and finally converges into the USC, with the increase of consolidation pressure.

Figure 4 shows effective stress change when clay of an initial specific volume f_0 (void ratio e_0) is remolded thoroughly (point B→point A) and is consolidated one-dimensionally. Remolding is a typical condition of the maximum disturbance, and a small amount of effective stress would remain after the remolding

Tsuchida et al. (1999) showed that the shear strength of remolded clay, s_{ur}, is given by the following equation with a normalized water content w/w_L :

$$s_{ur} = 1.4(w/w_L)^{-4.5} \quad (5)$$

Using the above equation, the strength of Point A in Figure 4, s_{uA}, is given as $1.4(e_0/e_L)^{-4.5}$. When the strength increment ratio in thoroughly remolded condition is given as $(s_u/p)_{REM}$, the effective stress at point A, p_A , is determined as follows:

$$p_A = s_{uA} / (s_u/p)_{REM} = 1.4(e_0/e_L)^{-4.5} / (s_u/p)_{REM} \quad (6)$$

Measured values of $(s_u/p)_{REM}$ for some marine clays ranges from 0.8 to 1.2 (Mikasa ,1988).

Point B is the effective stress condition of clay of f_0 on USC. From Eq.(4), the effective stress at point B, p_B, is given with $I_{sv0} = \ln f_0 / \ln f_L$, as follows;

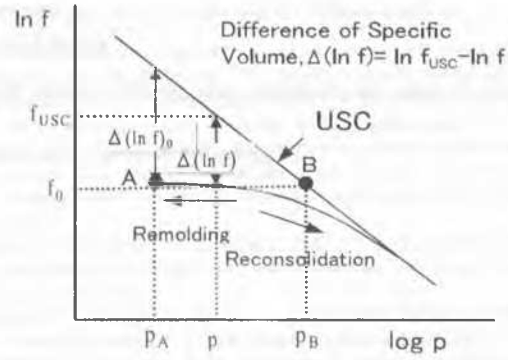

Figure 4. Standard compression curve and effective stress condition of remolded clay.

$$\log p_B = (1.47 - I_{sv0})/0.27 = 5.44 - 3.7\, I_{sv0} \quad (7)$$

The effect of the sample disturbance on e-log p relationship can be evaluated by disturbance ratio R, which is defined as the ratio of the intact effective stress to the residual effective stress after disturbance or remolding (Okumura,1974). In this case, R is given as p_B/p_A. When remolded clay at point A is consolidated one-dimensionally, the void ratio at each consolidation pressure becomes smaller than that on USC at the same consolidation pressure. The void ratio difference is determined by the reconsolidation ratio R_{CR}, which is defined as;

$$R_{CR} = \ln(p/p_A) / \ln R \quad (8)$$

where, p is the consolidation pressure and p_A is the initial effective stress when the consolidation starts. As shown in Figure 4, the difference of specific volume f from USC at the same consolidation stress is gradually reduced with increase of p accompanied with R_{CR}. Here the reduction ratio of specific volume r_f, is defined as follows;

$$r_f = \Delta(\ln f) / \Delta(\ln f)_0 \quad (9)$$

where, $\Delta(\ln f)_0$ is the difference of specific volume USC at the initial condition, and $\Delta(\ln f)$ is that after the consolidation starts. Okumura (1974) and Shogaki and Kaneko (1994) reported the change of e-log$p$ curves of marine clays when the clay sample is disturbed and reconsolidated. The relation between r_f and the reconsolidation ratio R_{CR} is plotted in Figure 5, which can be expressed by the following equations;

$$\left.\begin{array}{ll} r_f = 0.16(R_{CR} - 2.5)^2 & (R_{CR} \leqq 2.5) \\ r_f = 0 & (R_{CR} > 2.5) \end{array}\right\} \quad (10)$$

Using Equations (6)−(9) and (10), the standard compression curve from an initial void ratio SCC(e_0), can be written as:

$$\left.\begin{array}{l} I_{sv} = 1.47 - 0.27 \log p - h(p) \\ \text{when } p \leqq R^{2.5} p^*, \\ \quad h(p) = 0.0186(\ln R)\{\ln(p/p^*)/(\ln R) - 2.5\}^2 \\ \text{when } p > R^{2.5} p^*, \quad h(p) = 0 \\ \text{where, } I_{sv0} = \ln f_0 / \ln f_L, \quad p^* = 1.4\,(e_0/e_L)^{-4.5}/(s_u/p)_{REM} \\ \quad R = 10^{(5.44 - 3.7 I_{sv0})} \cdot (s_u/p)_{REM} / 1.4\,(e_0/e_L)^{-4.5} \end{array}\right\} \quad (11)$$

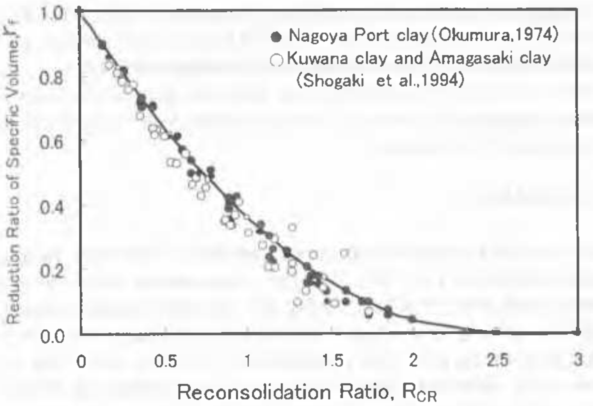

Figure 5. Relationship between r_f and R_{CR}.

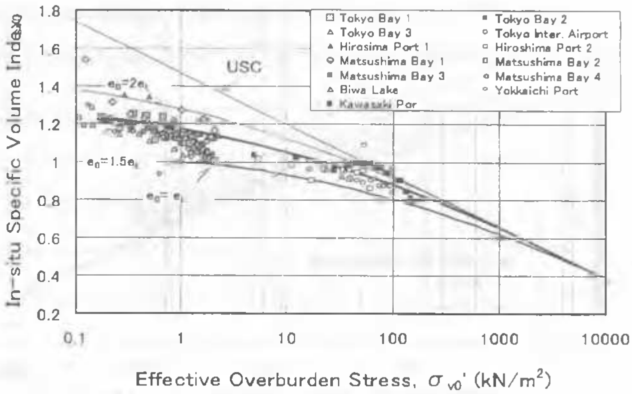

Figure 7. $I_{sv0}-\sigma_{v0}$' relationship (Holocene clay).

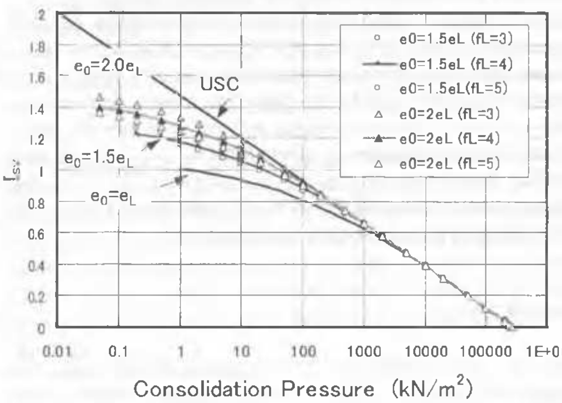

Figure 6. $I_{sv}-\log p$ relation of marine clay.

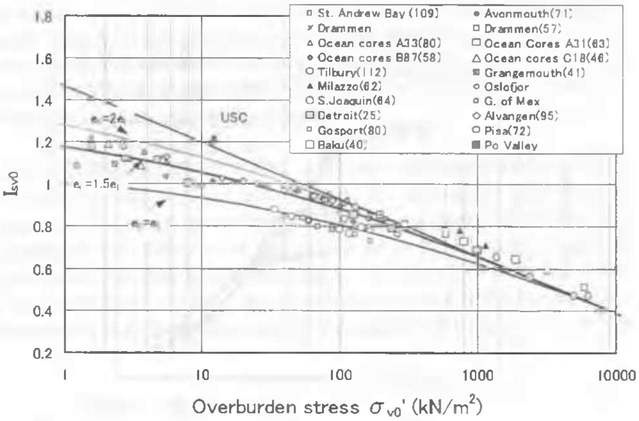

Figure 8. $I_{sv0}-\sigma_{v0}$' relationship of natural deposits (data from Skempton,1970).

3 INITIAL VOID RATIO OF MARINE CLAY AND NORMALIZED SCC FOR MARINE DEPOSIT

The field surveys of sea floor at Tokyo Bay, Hiroshima Bay, Matsushima Bay, and Biwa Lake showed that most of marine clays near the sea floor have the water contents of 1.5 to 2.0 times the liquid limits (Tsuchida and Gomyo,1995). Assuming that the initial void ratios e_0 at the beginning of consolidation of seabed is $1.5e_L$ or $2.0e_L$, standard compression curves SCC($e_0=1.5e_L$) and SCC($e_0=2e_L$) are calculated and are plotted in Figure 6 for the cases of $e_L=1.0$, $e_L=2.0$ and $e_L=3.0$. Although I_{sv}-log p relationships of SCC($e_0=1.5e_L$) and SCC($e_0=2e_L$) are different depending on the liquid limit of soil, the difference is not so large with ±0.1 difference of I_{sv}.

4 EVALUATION OF STRUCTURE BASED ON I_{SV}-OVERBURDEN STRESS RELATIONSHIP

As shown in Figure 1, when in-situ void ratio e_0 is larger than the value given by SCC, it is considered that the clay has a structure due to aging. Comparing the in-situ value of I_{sv0} with that on SCC at the same overburden pressure, the effect of structure can be evaluated quantitatively. The difference of specific volume index, ΔI_{sv0}, is written as follows;

$$\Delta I_{sv0} = (\ln f_0 - \ln f_{SCC})/\ln f_L = \ln(V_0/V_{SCC})/\ln f_L \qquad (12)$$

where, f_0 is in-situ specific volume, and f_{SCC} and V_{SCC} are specific volume and volume of soil on SCC at the same overburden stress, respectively. Equation can be written as;

$$\varepsilon_v = \ln(V_0/V_{SCC}) = (\Delta I_{sv0})(\ln f_L) \qquad (13)$$

where ε_v is volumetric strain to the volume of soil on SCCs. Using Equation (13), the in-situ degree of structure of soil can be indicated by volumetric strain.

4.1 *Holocene seabed*

Figure 7 is the relationship between the in-situ specific volume ratio I_{sv0} and the in-situ effective overburden stress σ_{v0}' at Holocene seabed. The average lines of standard compression curves SCC($e_0=e_L$), SCC($e_0=1.5e_L$) and SCC($e_0=2.0e_L$) in Figure 6 are indicated for the comparison. As shown in Figure 7, most of I_{sv0} of natural seabed are plotted around the SCC($e_0=1.5e_L$) line, when $p<40$kN/m². When $p>40$kN/m², some soils have larger in-situ specific volumes than those determined by SCC. This means that the void ratios of Holocene seabed in the shallow depth can be explained mainly by fundamental compression properties of clay and self-weight consolidation, and that no significant effect on void ratio was seen by the aging.

4.2 *Data collected by Skempton (1970)*

The first study on the in-situ void ratio - overburden stress of normally consolidated deposits was presented by Skempton (1970). Figure 8 shows reproduced $I_{sv0}-\sigma_{v0}$' relationship of 21 sites collected by Skempton. As shown in this figure, most of data are plotted around SCC($e_0=1.5e_L$), and some are plotted along SCC($e_0=e_L$). In the region of p>400kN/m², the values of in-situ specific volume index are larger than SCC and USC, suggesting that the structure had been formed during the sedimentation process and it had kept the void ratios be larger.

4.3 *Osaka Bay Pleistocene Clay*

Undisturbed samplings and soil tests of clay up to 400m depths were carried out at the site in Osaka Bay, where the over-

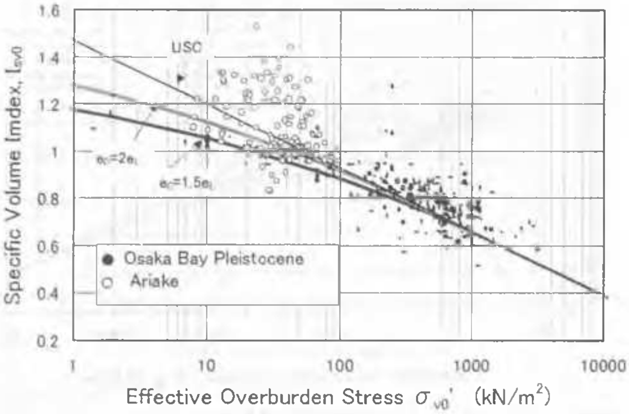

Figure 9. $I_{sv0} - \sigma_{v0}$' relationship of Osaka Bay Pleistocene clay and Ariake clay.

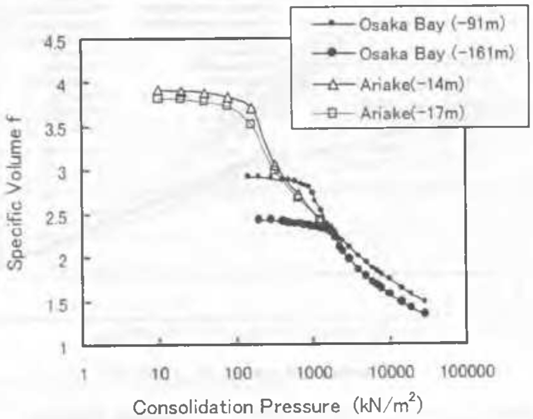

Figure10. Typical e-log p curve of Osaka Bay Pleistocene clay and Ariake clay.

consolidation ratios of clay layers are ranging from 1.0 to 1.5 in all the depth. The in-situ specific volume index I_{sv0} and the effective overburden stress are plotted in Figure 9. The values of I_{sv0} of Osaka Bay Pleistocene Clay are much larger than those determined by SCC(e_0=1.5e_L) or SCC(e_0=2.0e_L), which means that the clays in these area have larger void ratios or structures due to the aging effect during the sedimentation process. Taking the mean values of ΔI_{sv} in Figure 9 as 0.10 and the mean water content at liquid limit w_L as 80%, the expansive volumetric strain, ε_v, is calculated by Eq.(13) as ε_v = 0.10 ln (2.70×0.8+1) = 0.11. This means that, due to the aging effect, the volume of Osaka Pleistocene Clay layer are getting 11 % larger than those determined only by the gravitational consolidation.

4.4 *Ariake clay*

Ariake clay is widely deposited around Ariake Bay in Kyusyu Island and is known as typical sensitive clay in Japan. Torrance and Otsubo (1995) reported that most of Ariake clays have sensitivity larger than 16, with the maximum over 1000, and that the salt extraction by leaching is important factor causing large sensitivity.

The in-situ I_{sv0} - σ_{v0}' relationship of Ariake clay samples are plotted in Figure 9. The values of I_{sv0} of Ariake clay are extremely larger than those of SCC(e_0=1.5e_L) and SCC(e_0=2.0e_L). As the difference in I_s from SCC is more remarkable for clays with small liquid limits, the most probable explanation for this result is that Ariake clays sedimented under marine or brackish conditions with a high liquid limit and that the leaching occurred in the post-depositional process, which decreased the liquid limit, while giving the in-situ water content little change. Accordingly, in the case of Ariake clay, the structure was not developed by the aging, but the SCC was lowered by the decrease of liquid limit and consequently the value of I_{sv0} increase drastically.

Figure 10 show the typical *e*-log *p* curves of Osaka Bay Pleistocene Clay and Ariake clay obtained by the constant rate strain consolidation test. The extremely large compressibility is observed when the consolidation pressure gets larger than the consolidation yield stress p_c, which seems to be due to the destruction of the structure.

5 SUMMARY

The standard compression curve consists of ultimate standard compression curve, USC, and the compression curve from an initial void ratio, SCC(e_0). Using the specific volume index, I_{sv}, USC is shown as a simple relationship not dependent on the plasticity of clay. I_{sv}–log *p* relation of SCC(e_0) were also presented for different initial void ratios. By calculating SCC(e_0) with the conditions of e_0=1.5e_L and e_0=2e_L, the standard relationship between I_{sv} and the effective overburden pressure, σ_{v0}', was obtained for normally consolidated marine deposits.

The void ratios of Holocene seabed in the shallow depth can be explained mainly by SCC(e_0=1.5e_L) or SCC(e_0=2e_L) and no significant effect by aging are seen on the in-situ void ratio. As the in-situ values of I_{sv} of Osaka Bay Pleistocene clay are larger than those of SCC, the clays seems to have structure as much as 11% volumetric strain due to aging. The values of I_{sv} of in-situ Ariake clay were extremely larger than those of SCC. The cause of high I_{sv} value is considered to be the decrease of liquid limit by the leaching in the post-depositional process.

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