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Compressive Behavior of Sensitive Ariake Clays

Zhenshun HONG*
Takashi TSUCHIDA**

Synopsis

It has been well reported that the resistance of soil structure is the same important as stress history and initial water content in interpreting the mechanical behavior for most natural sedimentary soils. For assessing the effects of the resistance of soil structure on the mechanical behavior, Burland has proposed the so-called intrinsic compression line (ICL) and the sedimentation compression line (SCL) with introducing a normalizing parameter called the void index. However, the sensitive clays are not included in his study. The extensive data on sensitive Ariake clays are used in this study to investigate the compressive behavior through comparing with the ICL and the SCL. The main conclusions obtained in this study are summarized as follows.

1) For remolded Ariake clays, the relationship between void ratio and effective overburden pressure is consistent with the intrinsic compression line (ICL). The compressive behavior of remolded sensitive Ariake clays is not different from that of non-sensitive clays.
2) Most natural Ariake clays lie above well the sedimentation compression line (SCL). This is considered mainly due to the leaching. The leaching, that occurred during the post-depositional process, decreases the liquid limit of sensitive Ariake clays, consequently increases the in-situ void index.
3) The field void ratio of Ariake clays has a relative good relationship with the effective overburden pressure. The best-fit regression line can be expressed by the following equation: $\ln(1+e_0) = 2.1 - 0.54 \times \log(\sigma'_{vo})$. The above straight line is designated field state line (FSL) for Ariake clays.
4) The field state line (FSL), which shows much higher compressibility than that obtained in oedometer tests, can be explained by considering the lowering of liquid limit and the increase in effective stress during leaching process.

Key Words: Ariake clays, compression, field state line, leaching, liquid limit, void index

* Visiting Scientist of Soil Mechanics Laboratory, Geotechnical Engineering Division, Port and Harbour Research Institute

** Chief of Soil Mechanics Laboratory, Geotechnical Engineering Division, Port and Harbour Research Institute

3-1-1 Nagase, Yokosuka 239-0826, Japan

Phone: +81-468-445021 Fax: +81-468-444577 e-mail: hong@cc.phri.go.jp

港湾技術研究所報告
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鋭敏な有明粘土の圧縮特性に関する一考察

洪　振舜＊・土田　孝＊＊

要　旨

自然堆積土の圧縮性や強度特性は，堆積過程で形成される構造により大きな影響を受けている．これらの堆積構造を定量的に評価するパラメータとしてバーランドによる間隙指数が提案されているが，鋭敏粘土に関する間隙指数の適用性は調べられていない．有明粘土は鋭敏比が最大 1000 となる場合も報告されている日本の代表的な鋭敏粘土であるが，本報告は有明粘土の多数の圧密試験結果を用い，間隙指数による整理を行い，鋭敏粘土の圧縮特性を明らかにするとともにその原因を検討したものである．主な結論は次のようにまとめられる．

1) 練り返した有明粘土の圧密試験の結果を圧密圧力と間隙指数の関係として整理すると，バーランドによる固有圧縮線とほぼ一致した．練り返した有明粘土の圧縮挙動は，通常の粘性土の圧縮挙動とあまり違わないといえる．
2) 自然堆積状態の有明粘土の有効土被り圧と間隙指数の関係を求めると，ほとんどの場合，間隙指数はバーランドによる自然堆積圧縮線による値よりも大きかった．すなわち，有明粘土は通常の粘土に比べ，相対的にかなり高い間隙指数で堆積していることがわかった．
3) 有明粘土には，液性限界の違いによらず自然間隙比と土被り圧にユニークな関係がみられる．このことは，堆積時において一様に高い液性限界であった粘土が，塩分溶脱によって部分的に現在の液性限界に低下していると考えることで説明できる．

キーワード：有明粘土、固有圧縮曲線、液性限界、土被り圧、塩分溶脱、自然圧縮線、間隙指数

＊　土質部土性研究室客員研究員
＊＊　土質部土性研究室長
〒239-0826 横須賀市長瀬 3－1－1　運輸省港湾技術研究所
電話：0468-44-5021　Fax: 0468-44-4577　e-mail: hong@cc.phri.go.jp

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1. Introduction

Ariake Bay occupies about 1600 km^2 area on the western side of Kyusyu Island of Japan with its outlet of about 5 km wide (Ariake Research Group, 1965; Torrance and Ohtsubo, 1995). Ariake clays are widely deposited around Ariake Bay with an area of several hundreds of km^2. It has been well documented that the sensitivity of Ariake clays are very high (Ariake Bay Research Group, 1965). Ariake clays are the typical sensitive marine clays in Japan. Torrance and Ohtsubo (1995) have reported that most of Ariake clays have sensitivity larger than 16, with the maximum over 1000. Ariake Bay Research Group (1965) has revealed that the upper Ariake layer above 11*m* was deposited under a marine condition, while the lower Ariake layer below 11*m* was deposited under a brackish condition. The effect of salt removal has been reported to be an important factor causing large sensitivity for Ariake clays (Torrance and Ohtsubo, 1995; Ohtsubo et al., 1995).

The consolidation yield stress of natural Ariake clays is often larger than the effective overburden pressure (Hanzawa et al., 1990; Hong et al., 1998), although the site geology indicates the normal consolidation condition. Many researchers have indicated that the resistance of soil structure develops during depositional and post-depositional processes (Bjerrum, 1967; Locat and Lefebvre, 1985; Mitchell, 1986; Schmertmann, 1991). The resistance of soil structure is responsible for the difference in mechanical behavior of natural soils between the undisturbed state and the remolded state (Leroueil et al., 1979; Hanzawa and Adachi, 1983; Leroueil and Vaughan, 1990; Hong and Tsuchida, 1999). Because of the large sensitivity, Ariake clays seem to have highly developed structures. Although the importance of soil structure have been known qualitatively, the evaluation of the effect on mechanical properties have not been carried out in geotechnical engineering practice.

Burland (1990) has introduced a void index I_v to aid in correlating the compression characteristics of sedimentary soils with various plasticities. Based on the extensive data of reconstituted soils, Burland (1990) has found a so-called intrinsic compression line (ICL) as a frame for assessing the in-situ state of natural soils that have the structure. Burland showed that, by the normalization with the void index, there exists unique relationship between the in-situ void index and the effective overburden stress, σ_0', which is named sedimentation consolidation line (SCL). According to Burland, the difference in in-situ void index indicates the effect of soil structure, which is due to the aging effects such as cementation or chemical bonding during depositional and post-depositional processes.

In this study, the evaluation of soil structure of Ariake clays is carried out using the approach by Burland. The compression characteristics of remolded Ariake clays were investigated. Furthermore, the in-situ void index - effective overburden pressure relationships for natural Ariake clays were compared to the sedimentation compression line (SCL), which is obtained for natural deposits by Burland (1990). Then, the compression characteristics and the effect of soil structure of natural Ariake clays are discussed.

2. Compressibility of Remolded Ariake Clays

Burland (1990) showed that, most of the e - log p relationships of reconstituted clays can be normalized into one unique line by normalizing void ratios with the following parameters;

$$I_v = (e - e^*_{100}) / (e^*_{100} - e^*_{1000}) = (e - e^*_{100}) / C_c^* \tag{1}$$

where I_v is called void index and e^*_{100} and e^*_{1000} are void ratios when consolidation pressure are 100kPa and 1000 kPa, respectively. Burland showed that the unique I_v -effective overburden stress relationship is obtained from the reconstituted clays having initial water contents between $1.0w_L$ and 1.5 w_L, where w_L represents the liquid limit. The unique line named intrinsic compression line (ICL), can be expressed by the following equation (Burland, 1990).

$$I_v = 2.45 - 1.285 (\log \sigma'_v) + 0.015(\log \sigma'_v)^3 \tag{2}$$

where σ'_v is the effective vertical stress in kPa. When the oedometer tests are not performed on the remolded or reconstituted soils, the values of e^*_{100} and e^*_{1000} can be approximately calculated by the following equations (Burland, 1990).

$$C_c^* = 0.256e_L - 0.04 \tag{3}$$

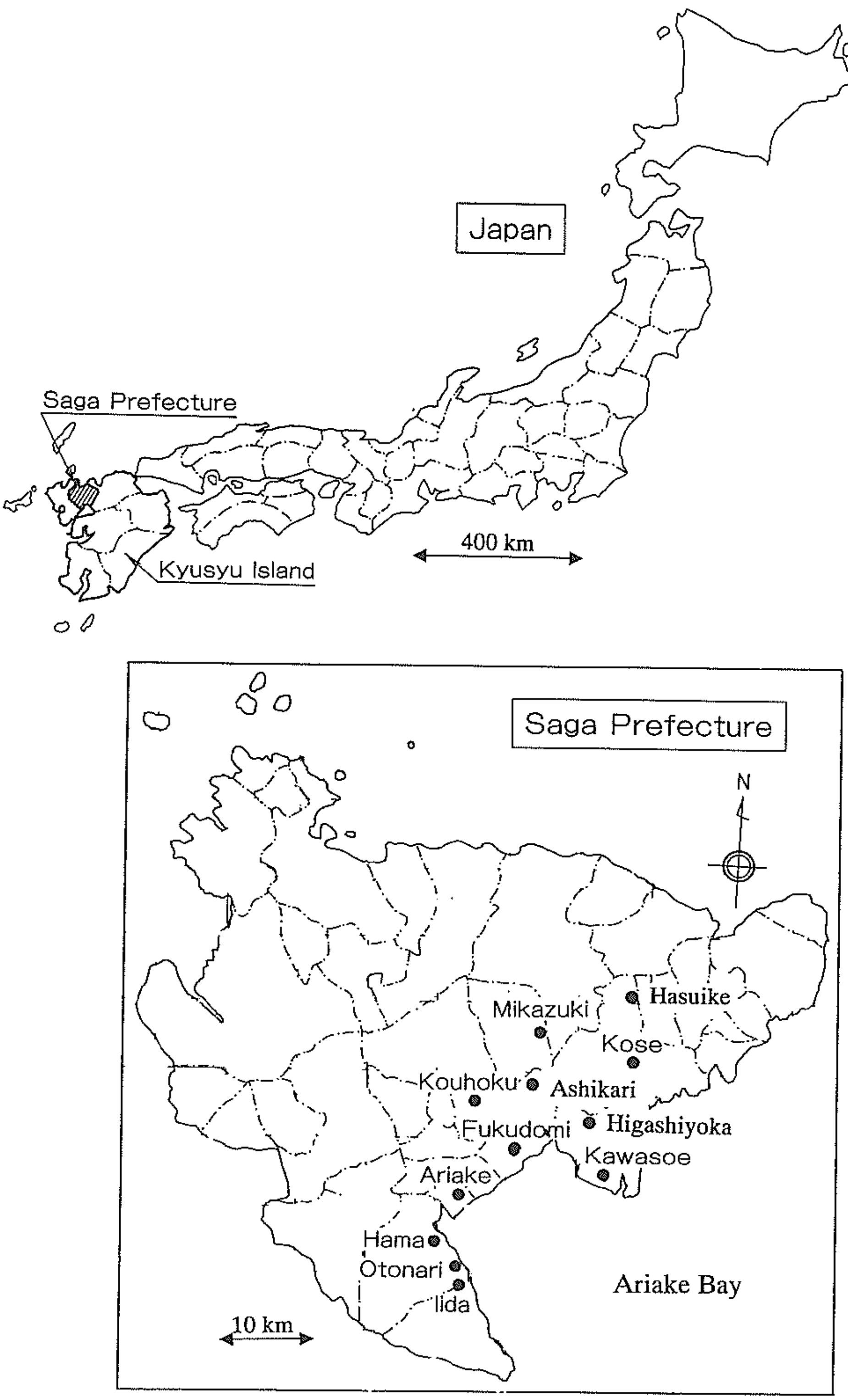

Figure 1 Sampling sites for Ariake clays

$$e^*_{100} = 0.109 + 0.679e_L - 0.089e_L^2 + 0.016e_L^3 \quad (4)$$

where e_L represents the void ratio at liquid limit.

The oedometer tests were performed on remolded Ariake clays sampled from several locations around Ariake Bay. The sampling sites for the remolded samples and the undisturbed samples used in this study are shown in **Figure 1**. The oedometer test data of remolded Ariake clays are used to verify the validity of the ICL shown in Equation 1 for Ariake clays. The basic properties of the remolded Ariake clays used herein are shown in **Table 1**. As shown in the table, the natural water content w_n is in the range of 1.0-1.5w_L. The relationship between the void index I_v and the effective vertical stress σ'_v for the remolded Ariake clays is shown in **Figure 2**, where the ICL proposed by Burland (1990) is also shown for comparison. The value of I_v is calculated using the values of e^*_{100} and e^*_{1000}, which were obtained by the oedometer test. It can be seen that the relationship of I_v against log σ'_v for remolded Ariake clays is in excellent agreement with the ICL.

Table 1 Physical properties of remolded Ariake clays

Site	Density of soil particles ρ_s (g/cm^3)	Water content w_n (%)	Liquid limit w_L (%)	Plastic limit w_P (%)
Ashikari Town	2.69	149	127	50
Ashikari Town	2.66	139	115	47
Ashikari Town	2.65	150	122	48
Higashiyoka Town	2.58	220	156	55
Ashikari Town	2.66	149	120	47
Kawasoe Town	2.62	175	149	56
Hasuike Town	2.59	165	116	46

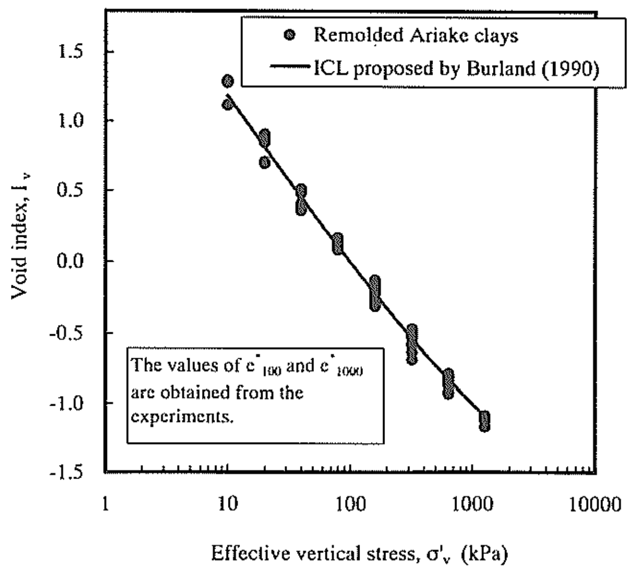

Figure 2 Relationship between void index and effective stress for remolded Ariake clays

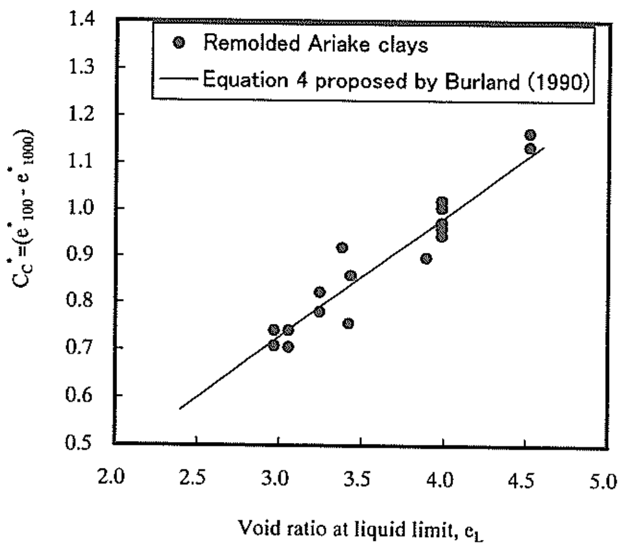

Figure 3 Relationship between $(e^*_{100} - e^*_{1000})$ and e_L for remolded Ariake clays

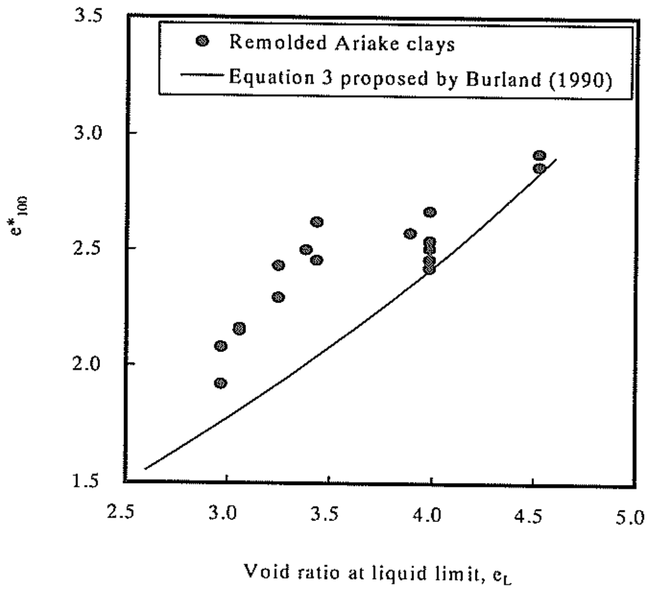

Figure 4 Relationship between e^*_{100} and e_L for remolded Ariake clays

Figures 3 and 4 show the relationships of C_c^* $(=e^*_{100}-e^*_{1000})$ against e_L and e^*_{100} against e_L for remolded Ariake clays, respectively. Comparing the experimental data with Equations 3 and 4 proposed by Burland (1990) shows that there is good agreement for the values of C_c^*. While the experimental data of e^*_{100} of remolded Ariake clays were larger than those given by Equation 3. This comparison is consistent with that discussed by Burland (1990), in which the experimental data of reconstituted Japanese marine clays published by Nakase et al. (1988) were used.

In summary, above analysis results indicate that the compression behavior of remolded Ariake clays is not significantly different from that of non-sensitive clays reported by Burland. The compression curves of remolded Ariake clays can be normalized using Equation 1.

3. Relationship between Void Index and Effective Overburden Pressure for Natural Ariake Clays

Skempton (1970) has presented the so-called sedimentation compression curves, relating void ratio to effective overburden pressure for a wide lithological range of argillaceous deposits, and he has reported that in all cases the data are derived from "normally-consolidated" deposits, strata that have never been under a pressure greater than that the existing effective overburden load. Excluded from the Skempton's study were sensitive/quick clays, diatomaceous clays, clays containing more than 5% organic matter as well as clays with a carbonate content of more than 25%. Based on the data published by Skempton (1970), Burland (1990) have proposed a so-called sedimentation compression line (SCL). The SCL is expressed in terms of I_{vo} versus the effective overburden pressure σ'_{vo} as shown in **Figure 5** after Burland (1990). The quantity I_{vo} is termed as the void index similar to I_v and defined as follows (Burland, 1990).

$$I_{vo} = (e_0 - e^*_{100}) \,/\, (e^*_{100} - e^*_{1000}) = (e_0 - e^*_{100}) \,/\, C_c^* \quad (5)$$

where e_0 represents the in-situ void ratio.

Extensive data of sensitive Ariake clays are used herein to investigate the relationship of I_{vo} versus log σ'_{vo} for Ariake clays. The data were obtained from the specimens sampled from various sites in **Figure 1** around Ariake Bay through different depths of 1.0*m* to 37.0*m*. For calculation of I_{vo}, Equations (3) through (5) were used. The data of the specimens from near the ground surface are excluded, because they seem to be affected by the desiccation. **Table 2** shows the basic properties of the Ariake clays used herein. It can be seen that the specimens have a wide range of liquid limit w_L varying from 40% to 140%.

Table 2 Basic properties of natural Ariake clays

Site	Depth m	Overburden pressure σ'_{vo} (kPa)	Density of soil particles ρ_s (g/cm³)	Natural water content w_n (%)	Liquid limit w_L (%)	Plastic limit w_P (%)	Initial void ratio e_0
Hama Town, Kashima City	4.0 ~ 19.0	20.9 ~ 87.7	2.56 ~ 2.66	74 ~ 117	72 ~ 117	32 ~ 51	1.86 ~ 2.98
Mikazuki Town, Ogi City	4.0 ~ 13.0	23.4 ~ 63.8	2.55 ~ 2.69	59 ~ 115	54 ~ 105	29 ~ 41	1.53 ~ 2.93
Fukudomi Town, Kishima City	2.0 ~ 15.0	11.9 ~ 71.5	2.57 ~ 2.68	62 ~ 149	44 ~ 103	22 ~ 49	1.64 ~ 3.82
Otonari Town, Kashima City	1.0 ~ 10.0	7.9 ~ 53.8	2.62 ~ 2.71	73 ~ 151	64 ~ 122	32 ~ 45	1.95 ~ 3.90
Ariake Town, Kishima City	2.0 ~ 37.0	10.3 ~ 172.2	2.58 ~ 2.69	51 ~ 146	87 ~ 129	36 ~ 50	1.36 ~ 3.84
Kose Town, Saga City	4.0 ~ 7.0	28.0 ~ 38.6	2.63 ~ 2.66	85 ~ 89	59 ~ 72	31 ~ 34	2.28 ~ 2.29
Kouhoku Town, Kishima City,	2.0 ~ 19.0	13.0 ~ 98.2	2.57 ~ 2.67	70 ~ 161	86 ~ 143	35 ~ 46	1.84 ~ 4.12
Kawasoe Town, Saga City,	3.0 ~ 17.0	22.4 ~ 98.1	2.63 ~ 2.69	55 ~ 99	54 ~ 98	29 ~ 39	1.47 ~ 2.33
Ilda Town, Kashima City,	2.0 ~ 5.0	12.8 ~ 20.9	2.57 ~ 2.69	123 ~ 164	91 ~ 104	51 ~ 60	3.17 ~ 4.17

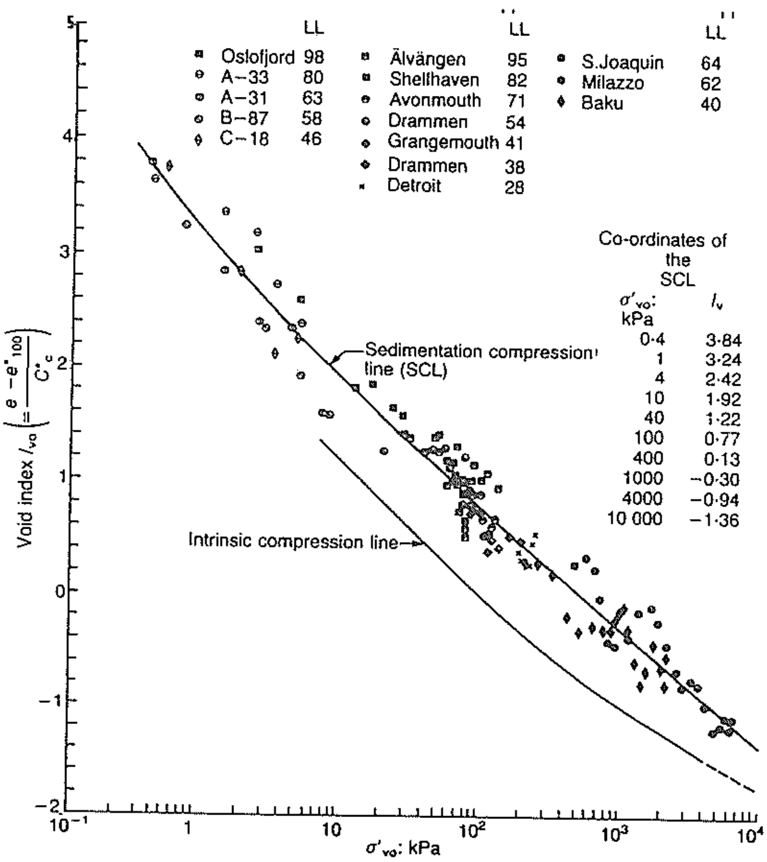

Figure 5 Sedimentation compression line (SCL) (after Burland, 1990)

Figure 6 shows the relationship between the natural water content w_n and w_L for the Ariake clays. It can be seen that most of the Ariake clays have a ratio of w_n/w_L, defined herein as normalized water content w^*, between 1.0 and 1.5. This result is consistent with that reported by Fujikawa and Takayama (1980).

The relationships of I_{vo} versus log σ'_{vo} of Ariake clays at various sites are shown in **Figure 7**, and compared with the ICL and the SCL proposed by Burland (1990). It can be seen that most of the Ariake clay data lie above the SCL. This is explained as mainly due to the leaching. It is well known that the shear strength of marine clay deposits is gradually reduced as the original salt content in the pore water decreases due to the leaching (Mitchell, 1993). It has been reported that the leaching has definitely occurred in some sites of Ariake deposits, and the reduction in salinity of pore water decreases the liquid limit and increases the sensitivity for Ariake clays (Torrance and Ohtsubo, 1995; Ohtsubo et al., 1995). The data of I_{vo} versus σ'_{vo} for Ariake clays are re-plotted by means of w_L as shown in **Figure 8**. It can be seen that at a given value of σ'_{vo} the higher the liquid limits, the closer to the SCL are the data of I_{vo} for Ariake clays. Furthermore, **Figure 9** shows the relationships of I_{vo} versus log σ'_{vo} with different ratios of normalized water content w^* ($=w_n/w_L$). It can be seen that for a given value of σ'_{vo}, the I_{vo} with higher value of w^* lies above the I_{vo} with lower value of w^*. The most probable explanation for above results is that the Ariake clays deposited under marine or brackish conditions had a high liquid limit during the process of deposition. The leaching occurred during the post-depositional process decreased the liquid limit, while the in-situ water content may have little change. That is, salt removal decreases the liquid limit, consequently increases the value of the normalized water content w^*.

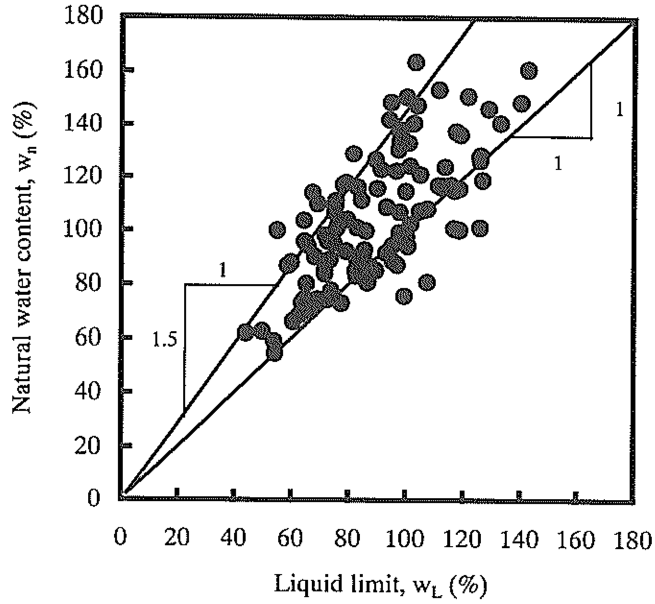

Figure 6 Relationship between liquid limit and natural water content for Ariake clays

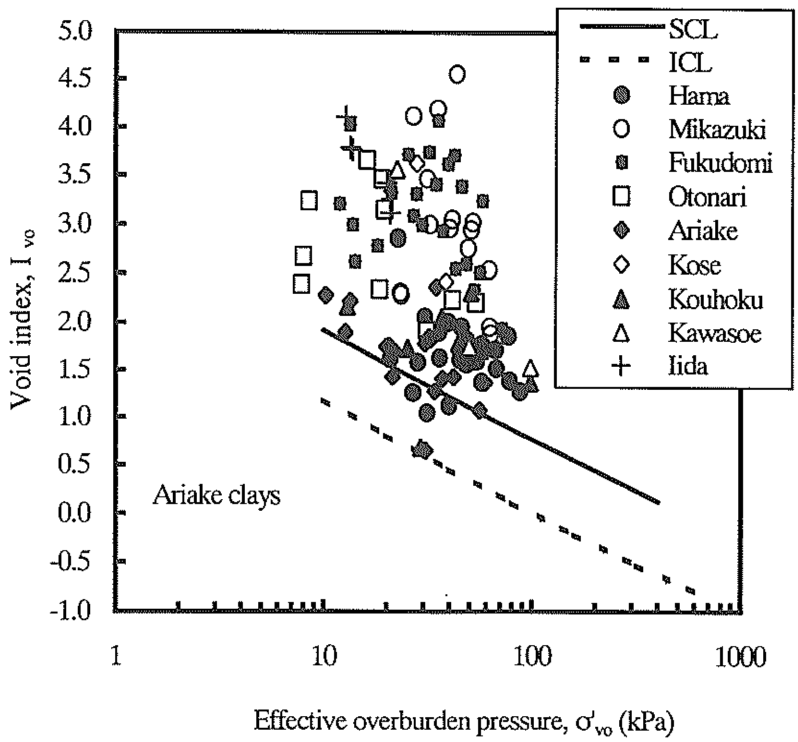

Figure 7 Relationship between void index and effective overburden pressure for Ariake clays

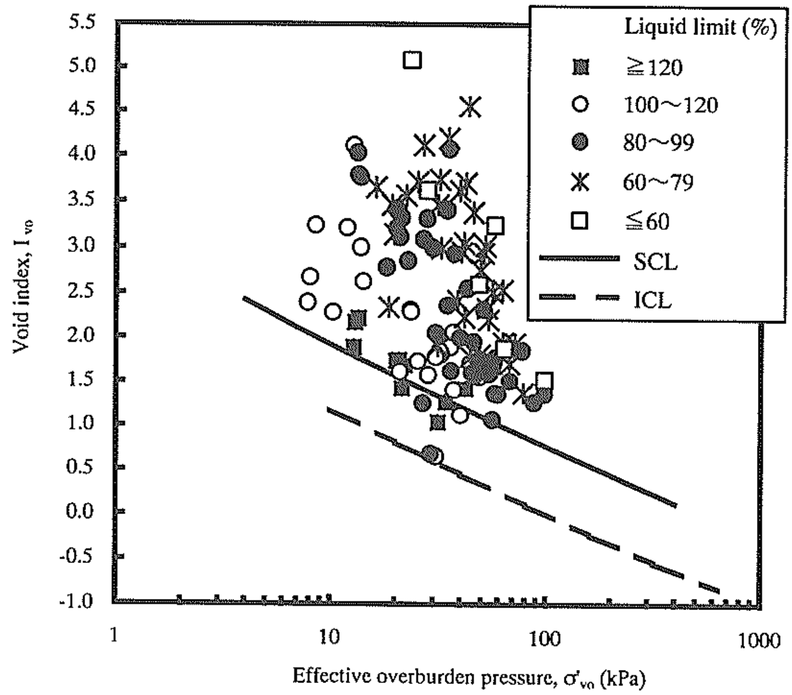

Figure 8 Relationship of I_{vo} and σ'_{vo} for Ariake clay with different liquid limit

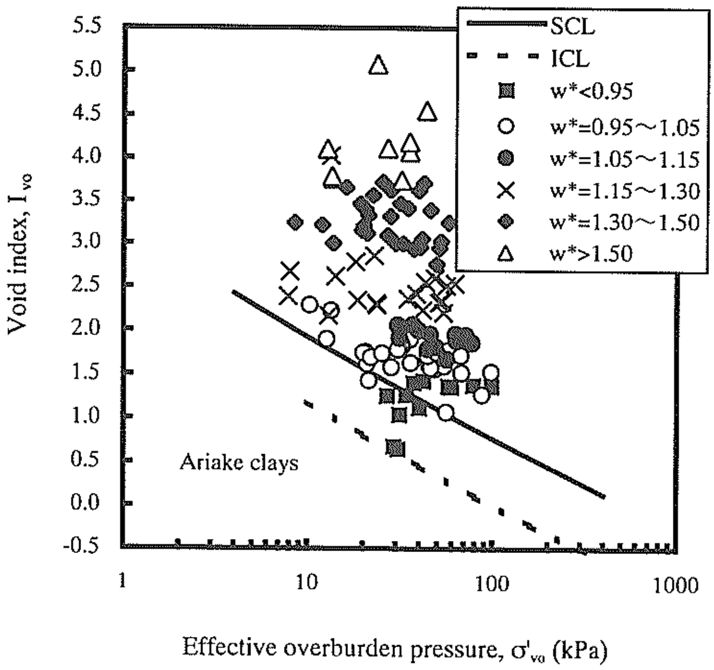

Figure 9 Relationship of I_{vo} and σ'_{vo} for Ariake clay with different w^*

From **Figure 9** it can be seen that the I_{vo} depends on the normalized water content. In fact, introducing Equations 3 and 4 into Equation 5, following equation can be obtained.

$$I_{vo}=(w^{*}-0.109/e_L-0.679+0.089e_L-0.016e_L^{2})/(0.256-0.04/e_L) \quad (6)$$

The above equation indicates that the I_{vo} depends on the normalized water content and the void ratio at liquid limit. However, with calculating the values of I_{vo} with different values of e_L ranging from 1 to 4, it is found that the I_{vo} varies little with the value of e_L. From the calculation results, the relationship I_{vo} and w^{*} can be expressed as following simple equation.

$$I_{vo} = 4w^{*}-2.5 \quad (7)$$

Equation (7) indicates that the in-situ void index increases linearly with the increase in normalized water content.

In addition, from **Figures 7 through 9** it can be seen that the various sedimentation curves related to I_{vo} versus log σ'_{vo} for Ariake clays converge with the increase in effective overburden pressure, in particular when σ'_{vo} is larger than about 50 kPa. This may be due to the depositional environment, because an overburden pressure of 50 kPa is responsible for the boundary at about 11m for the upper layer and the lower layer of Ariake clays. As aforementioned, the upper layer was deposited under high salinity of marine condition, whereas the lower layer was deposited under relative low salinity of brackish condition. Torrance and Ohtsubo (1995) have considered that the most probable leaching way for Ariake clays is leaching from below in responsible to excess water pressures in the underlying coarse sediments. However, they have also indicated that no evidence to support or reject the presence of excess ground water pressures for Ariake deposits in the past.

It should be mentioned that Burland (1990) has also reported that freshwater glacial lake clay lies above the SCL due to the presence of haematite, which has given rise to cementation between the particles. Den Hann (1992) has also reported a similar phenomenon for Canadian cemented clays. Torrance and Ohtsubo (1995) have considered that cementation remains the most plausible explanation for higher than expected undisturbed strengths found in high sensitivity marine Ariake clays. However, the evidence for cementation in Ariake clays is ambiguous. In our opinion, if the term cementation is referred to the cementing agents among particles or aggregations, it is considered that cementation is probably not an important factor responsible for the Ariake clays lying above well the SCL.

4. Relationship between In Situ Void Ratio and Effective Overburden Pressure for Natural Ariake Clays

As aforementioned, Skempton (1970) has presented the relationship between in situ void ratio and effective overburden pressure for many normally consolidated deposits. According to Skempton, it is concluded that at a given value of the effective overburden pressure the void ratio of a normally consolidated natural clay depends on the nature and amount of clay minerals present, as indicated by the liquid limit. The higher the liquid limit the larger is the void ratio (Skempton, 1970; Burland, 1990). For investigating the sedimentation state of Ariake clays, the relationships of e_0 against σ'_{vo} with different liquid limits for Ariake clays are shown in **Figure 10**. It can be seen that the data lie in a well defined continuous band and the relationships of e_0 versus σ'_{vo} are almost independent of w_L. The data of e_0 versus σ'_{vo} shown in **Figure 10** is replotted herein in the ln($1+e$)-log σ'_v plot as shown in **Figure 11**. Regression analysis gives the best-fit regression line as the following equation.

$$\ln(1+e_0) = 2.1-0.54\times\log\sigma'_{vo} \quad (8)$$

The coefficient of correlation for Equation 8 is 0.835, a little higher than that of the relationship between e_0 and log σ'_{vo} (i.e., 0.812). The line defined by Equation 8 is designated herein the field state line (FSL) for Ariake clays. From **Figure 11**, it can be seen that most of the data lie within the range $\ln(1+e_0)\pm0.2$ of the FSL.

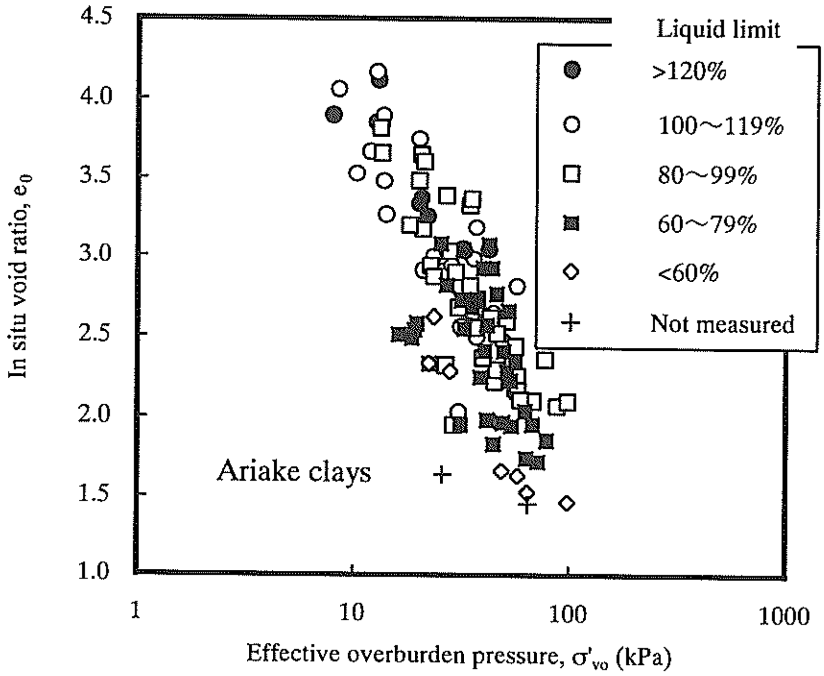

Figure 10 Relationship between in situ void ratio and effective overburden pressure for Ariake clays

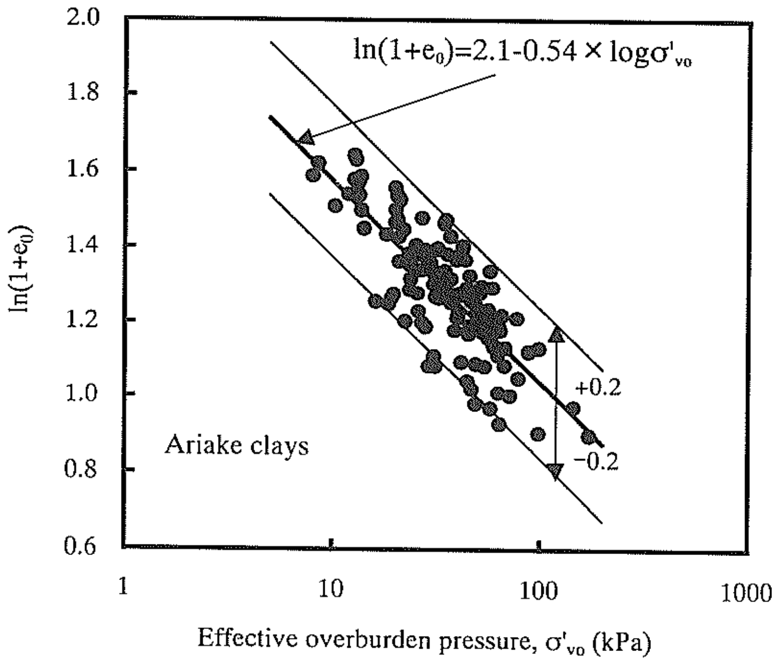

Figure 11 Field state line (FSL) for Ariake clays

The unique relationship of e_0 against σ'_{vo} for natural Ariake clays with different liquid limits may be explained as follows. The Ariake clays might have deposited at relative high values of w_L with a relative narrow variation band of w_L. That is, the sedimentation compression line (SCL) was relative higher responsible for higher liquid limit, as shown in **Figure 12.** Leaching occurred during the post-depositional process decreases the liquid limit by different extents for various sites and depths. Accompanying with the increase in effective stress, the sedimentation compression line for the leached Ariake clays lowers into that for lower liquid limit.

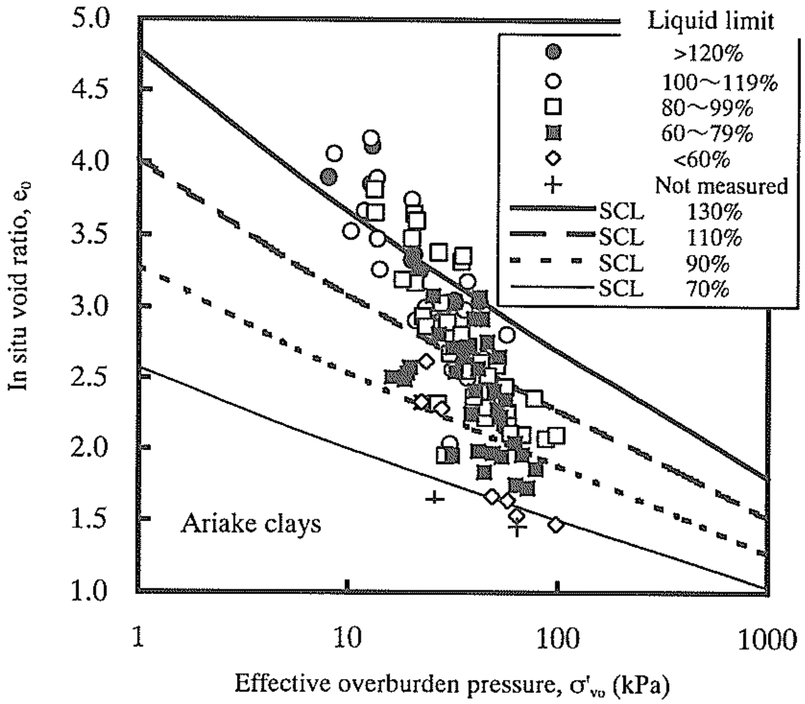

Figure 12 Comparison between e_0 against σ'_{vo} for Ariake clays and SCL with different liquid limit

5. Comparison between Field State Line and Compression Curves

Figures 13 and 14 show the typical oedometer test results for the upper and the lower layers of undisturbed Ariake clays, respectively. For comparison, the FSL is also shown in the same figures. It can be seen that the oedometer test data can be plotted by two straight lines in the $\ln(1+e)$-$\log \sigma'_v$ plot. The stress at the intersection point of the two straight lines is the consolidation yield stress, σ'_{yL}. The relatively steep slope of the line connecting the point (e_0, σ'_{vo}) at the effective overburden pressure and the point (e_{yL}, σ'_{yL}) at the consolidation yield stress indicates that the sensitive Ariake clays are easily disturbed during sampling and handling. This is consistent with the result reported by Hong et al. (1998). From **Figures 13 and 14,** it can also be seen that the consolidation yield stress is larger than the effective overburden pressure. The compression curves beyond the consolidation yield stress lie to the right of the FSL. The compressive behavior of undisturbed clays is quite different from that of field state line, even that the consolidation yield stress is only slightly larger than the corresponding effective overburden pressure. The gradient of the FSL is much larger than that of consolidation compression line of the undisturbed sample at the stress level larger than the consolidation yield stress. As aforementioned, the FSL is responsible for the leaching process in which the sedimentation compression line lowers from that with higher liquid limit to that with lower liquid limit. While the consolidation compression curves obtained from oedometer tests are responsible for the consolidation process with the liquid limit at present.

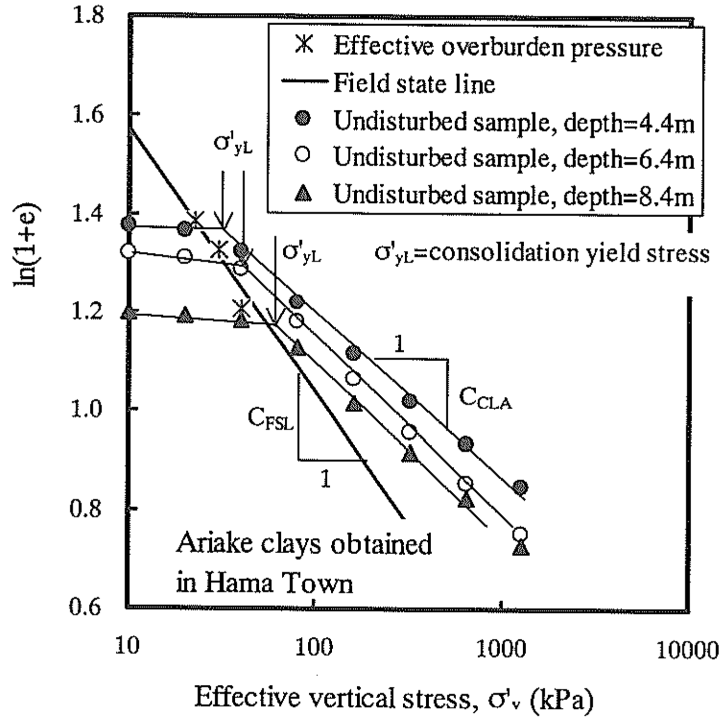

Figure 13 Typical oedometer test results of undisturbed upper Ariake clays

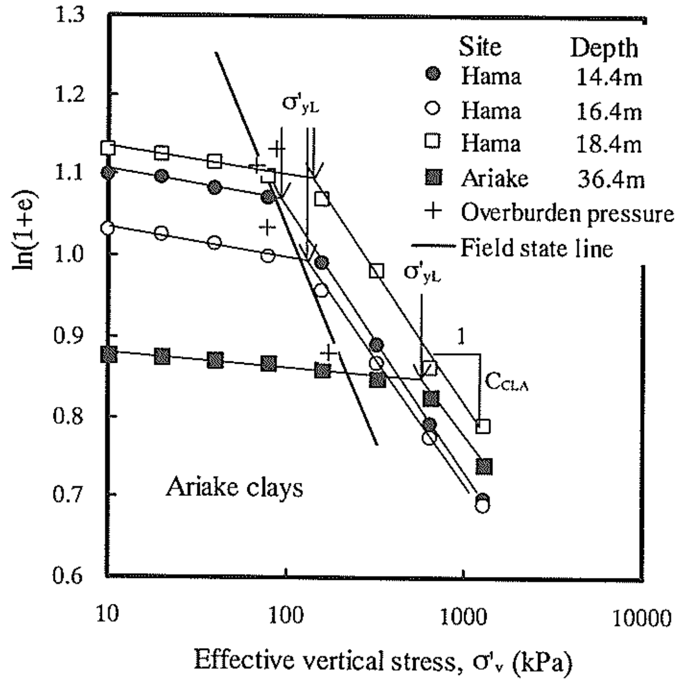

Figure 14 Typical oedometer test results of undisturbed lower Ariake clays

In summarizing the effect of leaching on the sedimentation compression curves for sensitive Ariake clays, the schematic plot is shown in **Figure 15**. If without leaching, the clays should deposit along the sedimentation compression line at higher liquid limit. During the leaching process, it is considered that the lowering of liquid limit and the increase in effective stress took place at the same time. Hence, the FSL is formed with a much higher compressibility than that obtained in oedometer tests.

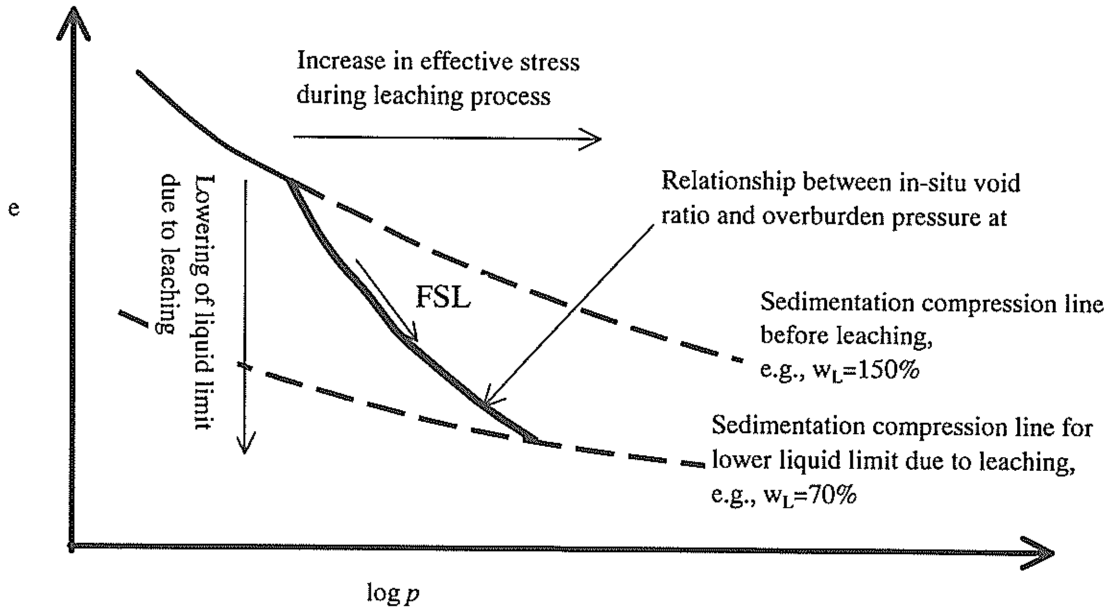

Figure 15 Schematic plot for effect of leaching on sedimentation compression line of Ariake clays

6. Conclusions

This study investigated the compressive behavior of sensitive Ariake clays using the intrinsic compression line and the sedimentation compression line proposed by Burland. The main conclusions obtained in this study are summarized as follows.

1) For remolded Ariake clays, the relationship between void ratio and effective overburden pressure is consistent with the intrinsic compression line. The compressive behavior of remolded sensitive Ariake clays is not different from that of non-sensitive clays.

2) Most natural Ariake clays lie above well the sedimentation compression line (SCL) proposed by Burland (1990). This is considered mainly due to the leaching. The leaching, that occurred during the post-depositional process, decreases the liquid limit of sensitive Ariake clays, consequently increases the in-situ void index.

3) The field void ratio of Ariake clays has a relative good relationship with the effective overburden pressure. The best-fit regression line can be expressed by the following equation: $\ln(1+e_0) = 2.1 - 0.54 \times \log(\sigma'_{v0})$. The above straight line is designated field state line (FSL) for Ariake clays.

4) The field state line (FSL), which shows much higher compressibility than that obtained in oedometer tests, can be explained by considering the lowering of liquid limit and the increase in effective stress during the leaching process.

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Symbols

C_{CLA}: slope of linear $\ln(1+e)$-$\log \sigma'_v$ compression line of undisturbed clay beyond consolidation yield stress

C_{CLR}: slope of linear $\ln(1+e)$-$\log \sigma'_v$ compression line of remolded/reconstituted clay

C_{FSL}: slope of FSL

e : void ratio

e_0: in-situ void ratio

e^*_{100}: void ratio of reconstituted clays for σ'_v = 100 kPa

e^*_{1000}: void ratio of reconstituted clays for σ'_v = 1000 kPa
e_L: void ratio at liquid limit
FSL: field state line for Ariake clays
ICL: intrinsic compression line
I_v: void index for e
I_{vo}: void index for e_0
SCL: sedimentation compression line
w_L: liquid limit
w_n: natural water content
w^*: normalized water content ($=w_L/w_n$)
σ'_v: effective vertical stress
σ'_{v0}: effective overburden pressure
σ'_{yL}: consolidation yield stress determined from $\ln(1+e)$-$\log \sigma'_v$ plot
ρ_s: density of soil particles