STRAIN RATE DEPENDENCY OF COHESIVE SOILS IN CONSOLIDATION SETTLEMENT

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ABSTRACT

It has been revealed from the long term consolidation test that the e - $\log p$ relation is linearly shifted with decrease in the strain rate in logarithm scale. The minimum strain rate measured by the conventional long term consolidation test is at most in the order of 10^{-9}s^{-1} . Question arises whether such a shift of the e - $\log p$ relation continues at even the infinite small strain rate, for example, smaller than 10^{-9}s^{-1} . To investigate the strain rate dependency of cohesive soil, the relaxation test was carried out for Osaka Pleistocene clays. It may be considered that in relaxation test, recoverable strain decreases due to decrease in acting pressure, and the irrecoverable strain equally increases, because the total strain remains constant. In this paper, assuming that the isotaches model can be applied to the irrecoverable strain, the strain rate dependency at very small strain rate was obtained from a series of relaxation tests. In this investigation the “strain rate dependency ratio” (SRDR) is defined as the ratio of the stress in the same ε or e under the objective strain rate, based on the strain rate of $3.3 \times 10^{-6}\text{s}^{-1}$. It is revealed that the SRDR at infinite small strain rate is about 0.7.

Key words: consolidation, isotaches model, long term consolidation test, Pleistocene clay, relaxation consolidation test, strain rate dependency (IGC: D5)

INTRODUCTION

Numerous research papers have reported that cohesive soils strongly exhibit viscous behavior in consolidation settlement in both laboratory and field: that is, even under constant effective stresses after dissipation of the excess pore water pressure, considerably large volume change is observed. This phenomenon is usually called “creep” or “secondary consolidation”. Some researchers have recently insisted that such behavior can be explained by the strain rate dependency, which is sometimes called “Isotaches model”, where a particular relation exists among effective stress (p'), void ratio (e) or strain (ε), and strain rate ($\dot{\varepsilon}$): i.e., $f(p', e, \dot{\varepsilon}) = 0$ or $f(p', \varepsilon, \dot{\varepsilon}) = 0$. It is reported that based on this dependency, the difference in the e - $\log p$ relation, particularly the yield consolidation pressures (p_c) measured by the conventional Incremental Load (IL) oedometer and Constant Rate Strain (CRS) oedometer tests with various strain rates can be consistently interpreted (Leroueil et al., 1985). Also, Imai and Tan (1992) and Tanaka (2005b) have shown that using inter-connected oedometer tests where several oedometer elements are linearly connected, the specimen in each element settles following the rule of the isotaches model.

It is known that the p_c value linearly decreases with decrease in strain rate in logarithm scale: that is, the e - $\log p'$ relation is shifted to the left side by decrease in

the strain rate. If such a decrease in p_c value was to continue infinitely with the decrease in strain rate, then the resulting p_c value would become smaller than even the in situ effective overburden pressure (p'_{vo}) under very small strain rate. Thus, it may be inferred that strain rate dependency gets eliminated at a strain rates less than a certain small value.

The minimum strain rate attained in the long term consolidation test is at most in the order of 10^{-9}s^{-1} , in spite of its duration being as long as half a year (Tanaka, 2005a). The strain rate in the CRS test is, of course, much larger than that of the above rate. Therefore, in such conventional consolidation tests, it is not feasible to examine whether the limitation of the strain rate dependency exists in very small strain rates or not.

The strain rate dependency at very small strain rates in this paper was obtained by the relaxation test, where the stress reduction was measured under the constant strain. Assuming that the isotaches model can be applied to the irrecoverable strain, the strain rate dependency at very small strain was obtained from the relaxation test. This test was able to achieve the strain rate of as small as 10^{-11}s^{-1} . It is found that when the strain rate is smaller than 10^{-9}s^{-1} , the strain rate dependency disappears. The p_c at strain rates less than 10^{-9}s^{-1} is about 0.7 times as large as that at $3.3 \times 10^{-6}\text{s}^{-1}$. This paper will discuss the meaning of this ratio of 0.7, referring to the data obtained by a series of site investigations in the Osaka basin.

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Fig. 1. Strain- $\log p'$ relation measured by CRS test, where the strain rate is changed (after Tanaka, 2005a)

Fig. 3. Strain Rate Dependency Ratio (SRDR) obtained from the CRS tests (after Tanaka, 2005a)

Fig. 2. Determination of Strain Rate Dependency Ratio (SRDR) for the Long Term Consolidation test

REVIEWS OF THE STRAIN RATE DEPENDENCY

Figures 1, 3 and 4 are referred from Tanaka (2005a), indicating the strain rate dependency of consolidation behavior for the Osaka basin Pleistocene clays. It can be seen from Fig. 1, where the strain rate was changed in the CRS test, that ε is not uniquely defined by p' alone, but this relation is governed by the strain rate. As noted by Leroueil et al. (1985), the relation between ε and $\log p'$ in Fig. 1 gets shifted in a parallel manner due to the change in $\dot{\varepsilon}$. If the pressure is normalized by the p_c value in different $\dot{\varepsilon}$, the e or $\varepsilon - \log p'$ relation can be uniquely expressed by a single line. In this paper, the term “strain rate dependency ratio” (SRDR) is the ratio of the stress in the same e or ε under the objective strain rate, based on $\dot{\varepsilon}$ of $3.3 \times 10^{-6} \text{ s}^{-1}$ ($0.02\%/\text{min}$), as illustrated in Fig. 2. In this case, the SRDR at a strain rate of $\dot{\varepsilon}_b$ can be expressed as p_b/p_a .

In the Osaka basin, a total of 14 marine clay layers have been found, including the Holocene clay, which is deposited just below the sea bed (Itoh et al., 2000; Tanaka et al., 2004). Figure 3 shows SRDR for various

Pleistocene clay layers in the Osaka bay, where CRS1 is a test at the constant strain rate throughout the CRS test, while CRS2 is a test where strain rate changes during the test, as shown in Fig. 1. It should be noted that CRS2 data series were obtained from the same specimen, whereas CRS1 data series were obtained from different specimens. Since the naturally deposited clay is not homogeneous, its behavior inevitably varies, resulting in a much larger scatter of the strain rate dependency in the CRS1 data, compared to that in the CRS2 data.

The geotechnical properties such as p'_{vo} , deposit age and index properties for marine clay layers in the Osaka basin considerably vary (Tanaka et al., 2004). However, any significant differences in the strain rate dependency among these layers are not identified. The above facts suggest that these properties do not have strong influence on the strain rate dependency. It should be noted, however, that the dependency of the strain rate considerably changes in various soil deposits in different areas (Tanaka et al., 2000).

The dependency of the strain rate in the Long Term Consolidation (LTC) test is similar to that in the CRS test, as shown in Fig. 4. Here, the strain rate dependency ratio (SRDR) was obtained from the LTC, as defined in Fig. 2. In the LTC test, the effective vertical stress after the dissipation of the excess pore water pressure is constant, as indicated by a vertical bold arrow in Fig. 2. As time elapses, the strain rate becomes gradually smaller in the LTC test. In Fig. 2, the pressure of p_b at a strain rate of $\dot{\varepsilon}_b$ corresponds to “ p_a ” on the equi-strain line of $3.3 \times 10^{-6} \text{ s}^{-1}$. The SRDR at $\dot{\varepsilon}_b$ can be obtained as p_b/p_a , where p_b is the LTC pressure.

Since the number of points obtained by the LTC test using various samples in Fig. 4 is so large, the strain rate dependency measured by the LTC test are indicated by ranges with the standard deviation ($\pm \sigma$). In the figure, P_r is the intensity index of consolidation pressure defined by $(p - p'_{vo}) / (p_c - p'_{vo})$, where p and p_c are consolidation pressure in the LTC test and yield consolidation pressure, respectively. n is the number of test. As indicated in both

Figs. 3 and 4, it is apparent that the strain rate dependency is related linearly with the $\dot{\epsilon}$ in logarithm scale. In addition, the same gradients of about 0.07 were obtained from the CRS as well as LTC tests. The question is whether such strain dependency still continues even at strains rates smaller than 10^{-9}s^{-1} .

GEOTECHNICAL PROPERTIES OF SAMPLES USED

All samples used in this investigation were retrieved from the Osaka bay underlying a water depth of 20 m. The sampling site is located about 8 km off the main land. All tested samples are Pleistocene clays and their main geological properties are indicated in Table 1, where ρ_s , w_n , w_L , w_P , I_p and e_o are respectively the density of soil particles, natural water content, liquid limit, plastic limit, plasticity index and void ratio. More information on these clays can be referred to, for example, Tanaka et al. (2004). Samples located shallower than 120 m from the sea bottom were retrieved using a hydraulic piston sampler and deeper samples were obtained by a rotary core tube sampler (for more details, refer to Tanaka et al., 2002).

Fig. 4. Comparison of Strain Rate Dependency Ratio (SRDR) from CRS and Long Term Consolidation tests (after Tanaka, 2005a): In the figure, P_r is a relative consolidation pressure, as defined by $(p-p'_{vo})/(p_c-p'_{vo})$, where p_c , p and p'_{vo} are the yield consolidation pressure at $3.3 \times 10^{-6}\text{s}^{-1}$, consolidation pressure and the in situ effective overburden pressure, respectively and n is the number of test

UNLOADING TEST

Before describing the relaxation test, results from unloading test will be mentioned. This test will provide important data to interpret test results from the relaxation test. The test was carried out using the CRS test apparatus, where the size of the specimen is 60 mm in diameter and 20 mm in initial height. The bottom of the oedometer is undrained and equipped with a piezometer to measure the excess pore pressure generated by applying the constant strain. The upper part of the specimen is free to drainage. A back pressure of 200 kPa was applied to saturate the specimen. The average effective stress (p') in the specimen is calculated by Eq. (1), assuming that the excess pore water pressure is distributed in a parabolic manner.

$$p' = p - 2/3u \quad (1)$$

where, p and u are respectively the applied total pressure and the pore water pressure measured at the undrained side. The strain rate applied is $3.3 \times 10^{-6}\text{s}^{-1}$ ($0.02\%/min$) for both loading and unloading tests.

A typical example of the $e-\log p'$ relation from the loading and unloading tests is shown in Fig. 5. In this case, the unloading was carried out at four different strain levels, i.e., $\epsilon = 2, 7.5, 15$ and 22% . In these strain levels, the unloading test for $\epsilon = 2\%$ was carried out at around the p_c value; for other three strain levels, the

Fig. 5. An example of $e-\log p'$ relation for loading and unloading tests

Table 1. Geotechnical properties of soils used in the test

Layer	Sample No.	Depth (m)	ρ_s (g/cm^3)	w_n (%)	w_L (%)	w_P (%)	I_p	e_o
Ma12	T42	52	2.640	74.2	98.7	38.7	60.0	1.975
Ma11	T68	80	2.720	50.8	74.7	25.5	49.2	1.385
Ma10	T90	108	2.709	48.4	91.8	34.5	57.3	1.313
Ma9	D46	137	2.682	58.1	99.7	36.1	63.6	1.559
Doc5	D75	167	2.704	52.8	104.8	36.5	68.3	1.421

ρ_s : density of soil particles, w_n : natural water content, w_L : liquid limit, w_P : plastic limit, I_p : plasticity index, e_o : void ratio

Fig. 6. Change in void ratio due to the unloading for the same soil

stress condition is at the normally consolidated (NC) state. The $e-\log p'$ relation from the unloading test is shown in Fig. 6, where the unload stress is normalized by the pressure at the start of the unloading test ($p'_{\max}$). In the vertical axis, the change in void ratio from the start of the unloading test (Δe) is plotted. It can be seen in this figure that the relation between Δe and $p'/p'_{\max}$ from the unloading test can be drawn by a single line even for different strain levels, regardless of whether the stress level is either at the p_c value or in the NC state. The same tests were carried out for samples retrieved from other soil layers and the similar test results were obtained, indicating that particular relation exists between Δe and $p'/p'_{\max}$ in the unloading process for a specific soil type.

It is apparent, however, that the Δe and $p'/p'_{\max}$ relation is different for different soils, as seen in Fig. 7. This figure indicates the Δe and $p'/p'_{\max}$ relation at $\varepsilon > 20\%$. It should be kept in mind that the relation between Δe and $\log(p'/p'_{\max})$ is not linear. The secant of this relation, which corresponds to the swelling index (C_r), is the smallest at the start of the unloading test, and then gradually becomes larger with the increase in swelling. The order of C_r in the small stress part of the unloading curve is between 0.05 and 0.10, being considerably smaller compared to compression index (C_c) derived in the loading process at the NC state.

RELAXATION TEST

The relaxation test was conducted using also the CRS equipment. The testing procedure will be explained using Fig. 8. The specimen is consolidated under constant strain rate (in this test, $\dot{\varepsilon} = 3.3 \times 10^{-6} \text{ s}^{-1}$) in the CRS test apparatus until the determined strain level for the relaxation test reaches. Then, the loading was stopped and the relaxation test was started, by keeping the strain constant. In this stage, acting force on the specimen and

Fig. 7. Relation between change in void ratio and unload stress for various soils

Fig. 8. An example of $e-\log p$ relation for CRS and relaxation tests

the excess pore water pressure were measured (in fact, the excess pore water pressure quickly reduced to zero for all relaxation tests). The relaxation tests were, in most cases, carried out at four strain levels: for example, these strain levels are 0.8, 1.2, 5.0 and 10.0% as shown in Fig. 8. The duration of the relaxation test was usually 2 days. After 2 days of relaxation duration, the loading was resumed at the constant strain rate.

A typical test result is shown in Fig. 9, where the stress reduction is normalized by the $p'_{\max}$, which is the consolidation stress at the start of the corresponding relaxation test. It is very interesting to note that if the stress reduction is plotted in the normalized form, behavior of stress reduction can be uniquely related to the elapsed time, regardless of the stress or strain level at the start of the relaxation test. However, this relation is clearly different between the OC and the NC states, unlike in the unloading test (see Fig. 6).

Using a sample from the Ma12 layer, the effect of strain rate before the start of the relaxation test was examined. Test results are shown in Fig. 10. As already described earlier, the ε and $\log p'$ relation gets shifted to the right hand side with the increase in the strain rate, due to the

Fig. 9. Stress reduction obtained from the relaxation test

Fig. 11(a). Stress reduction at fast strain rate, i.e., $\dot{\epsilon} = 3.3 \times 10^{-5} \text{ s}^{-1}$

Fig. 10. Comparison of stress relaxation test results caused by different strain rate

Fig. 11(b). Stress reduction at moderate strain rate, i.e., $\dot{\epsilon} = 3.3 \times 10^{-6} \text{ s}^{-1}$

strain rate dependency. However, the shape of ϵ and $\log p'$ relation does not change. If the stress reduction is plotted in the form of $p'/p'_{\max}$ with the elapsed time, similar to Fig. 9, then $p'/p'_{\max}$ can be clearly correlated to the time (see Figs. 11 (a) through (c)). However, these relations are different according to the strain rates applied before the start of the relaxation test (see Fig. 12 where the relaxation test started at ϵ of 5%). When the pre-relaxation strain rate is faster, the resulting stress reduction becomes larger. This is because as the strain rate is greater, larger stress can be sustained at any specified strain. Similar findings were also presented by Yoshikuni et al. (1994).

From these test results from the unloading and relaxation tests, all data have been prepared to derive the strain rate dependency. Assumptions for obtaining the strain rate dependency from these tests are as follows:

- 1) The total strain (ϵ_t) consists of two components: i.e., recoverable or elastic strain (ϵ_e) and irrecoverable or plastic strain (ϵ_p), $\epsilon_t = \epsilon_e + \epsilon_p$.
- 2) The ϵ_e component can be obtained by the unloading test. If the process of unloading is purely elastic, e (or ϵ) - $\log p'$ relation in both unloading and reloading must coincide. However, as shown in Fig. 5, both

Fig. 11(c). Stress reduction at slow strain rate, i.e., $\dot{\epsilon} = 3.3 \times 10^{-7} \text{ s}^{-1}$

relations are somewhat different, i.e., showing a hysteresis loop. This point will be discussed later in more detail.

- 3) The isotaches model can be applied to only ϵ_p (see for example, Nash, 2001; Den Haan and Kamao, 2003). As shown in Figs. 6 through 9, generated strain in the unloading process (elastic strain) is very small

Fig. 12. Comparison of stress reduction and time relations for different strain rate at start of the relaxation test

compared to the strain yielded in the loading process. Therefore, it is apparent that during the loading process in the NC state, distinction of ε_t and ε_p is not necessary to apply the strain rate theory in practice. In fact, Leroueil et al. (1985) and Tanaka (2005a, 2005b) have indicated that the strain rate dependency apply to the total strain, instead of the plastic strain (i.e., see Figs. 1, 3 and 4).

Using the above assumptions, the ε_p in the relaxation test can be calculated. The value of ε_t is zero in the whole process of the relaxation test, but because of stress reduction, negative ε_e is generated according to the elapsed time. In another word, the same amount of ε_e , but positive strain of ε_p is yielded in the relaxation test (Leroueil and Hight, 2003). The stress reduction ($p'/p'_{\max}$) in the vertical axis of Figs. 9 and 11 ((a) through (c)) can be related by reduction of Δe from the unloading test (Figs. 6 and 7). Finally, relation between $p'/p'_{\max}$ and elapsed time for NC state in the relaxation test can be transformed into the ε_p and time relation. As a typical example, Fig. 13 shows the relation between ε_p and the elapsed time, obtained from the relaxation test for Ma10, where the strain rate at start of the relaxation test is $3.3 \times 10^{-5} \text{ s}^{-1}$.

Comparing the relation between ε and elapsed time obtained by the LTC test, the following interesting points can be found in Fig. 13: Until 80 min., the strain linearly increases with the log time, except for the beginning part. After 80 min., however, the strain becomes gradually smaller, and after 900 min, additional strain is not generated any more. Such behavior can not be found in the LTC test where the load duration is as long as half a year (see Tanaka, 2005a).

From the relation between ε_p and time in Fig. 13, the strain rate can be calculated. The calculated strain rate can be also correlated to the strain rate dependency ratio (SRDR) defined in Fig. 14. The difference between Figs. 2 and 14 is that the vertical stress is plotted against ε_p , and the ε_p increases in the relaxation test where the total strain is constant. The value of p_a at the reference strain rate $\dot{\varepsilon} = 3.3 \times 10^{-6} \text{ s}^{-1}$ increases with decrease in the pressure, as

Fig. 13. Irrecoverable (or plastic) strain caused by the relaxation test

Fig. 14. An illustration for calculation of the Strain Rate Dependency Ratio (SRDR) from the relaxation test

illustrated in Fig. 14. All data for Ma10 is plotted in Fig. 15, together with points from Fig. 3, where the SRDR was obtained by CRS test. It can be observed from the figure that the data measured from the relaxation test follow data from CRS at relatively large strain rate. This means that the isotaches model can only not interpret test results from the CRS with different strain rates, but can also consistently explain those from the relaxation test. However, when $\dot{\varepsilon}$ is less than $3.3 \times 10^{-8} \text{ s}^{-1}$, the SRDR is somewhat smaller than that obtained by CRS or the long term consolidation test. This discrepancy may be caused by the deriving method of ε_e . In this study, it is assumed that ε_e can be measured by the unloading test of the CRS. However, as shown in Fig. 5, there exists hysteresis in the relation of e -log p in the unloading and reloading processes. And also the C_r is not linear, but considerably dependent on pressure ratio ($p'/p'_{\max}$) (see in Fig. 6). It is doubtful whether the strain yielded by unloading is the elastic at every stress level. It is inferred that as a result from the overestimation of ε_p (or $-\varepsilon_e$) at small $p'/p'_{\max}$, large strain rate dependency could be calculated at small

Fig. 15. Strain Rate Dependency Ratio (SRDR) measured by the relaxation test

Fig. 16. An example of OCR profiles for the Osaka Holocene and Pleistocene clays (after Tanaka et al., 2004)

strain rate. Although there is uncertainty in the derivation of ϵ_e from the unloading test, the strain rate dependency is not prominent at smaller strain rate than 10^{-9}s^{-1} , whose strain rate is the minimum rate for the LTC test. And the strain rate dependency ratio (SRDR) at these strain rates is 0.7 (see Fig. 15).

Let us consider the meaning of this ratio, 0.7. Figure 16 shows OCR of a site investigation at the Osaka bay (see Tanaka et al., 2004). It may be noted that the vertical axis is indicated by the intensity of p'_{e0} at the sampled depth, where the p'_{e0} of 3 MPa corresponds to about 400 m depth from the sea bed. All OCR's were obtained by the CRS test with a strain rate of $3.3 \times 10^{-6}\text{s}^{-1}$. At the Osaka bay, a total of 14 marine clay layers were found, which were deposited from 1.1 million years ago for the oldest layer (Ma0), and in the Holocene age for the youngest layer just below the sea bed (Ma13) (Itoh et al.,

2000). Although there are still arguments whether these clays are overstressed in the past or not, it is believed by most researchers that they have not experienced the pressure larger than the present p'_{e0} , that is, they are mechanically normally consolidated clay. Also, it has been extensively accepted that the OCR greater than unity may be created by such factors as chemical or/and ageing effects during the long period after their deposit.

As can be seen in Fig. 16, OCR values are scattered in some ranges from 1.1 to 1.8 for most data. It has been found by the investigation using the cone penetration test (Tanaka et al., 2003) that such a scatter is not caused by sample disturbance, but mainly due to local variation of consolidation properties. The average OCR in Fig. 16 is about 1.4, and this number corresponds well to the inverse number of the strain rate dependency ratio at infinitely small strain rate, as shown in Fig. 15, i.e., $1/0.7 = 1.43$. This fact means that the OCR is only effective to relatively faster strain rate, but at very small strain rate, apparent high OCR disappears and they behave like a normally consolidated clay layer.

CONCLUSIONS

The strain rate dependency for Osaka Pleistocene clays was studied by the relaxation test, where the specimen was kept at a constant strain. The following interesting points were found:

- 1) The minimum strain rate measured by the long term consolidation test is at most in the order of 10^{-9}s^{-1} , even though the duration of loading is as long as half a year (from the previous study, Tanaka, 2005a).
- 2) The relation between $p'/p'_{\max}$ and Δe for unloading test is uniquely defined regardless of strain or stress levels at the start of the unloading test, where $p'_{\max}$ is the consolidation pressure at the start of the unload test, and Δe is the change in void ratio.
- 3) In addition, a unique relation can be found between $p'/p'_{\max}$ and time from the relaxation test, where $p'_{\max}$ is the consolidation pressure at the start of the relaxation test. However, the different relation is measured for overconsolidated and normally consolidated states.
- 4) Assuming that the isotaches model can be applied to the irrecoverable strain, the strain rate dependency has been obtained. This strain rate dependency fairly agrees with that from the CRS test at the moderate strain rates.
- 5) The strain rate dependency measured by the relaxation test disappears at the strain rates smaller than 10^{-9}s^{-1} . The "strain rate dependency ratio" (SRDR) is defined as the ratio of the stress in the same e or ϵ under the objective strain rate, based on the strain rate of $3.3 \times 10^{-6}\text{s}^{-1}$ (0.02%/min). The SRDR at strains smaller than 10^{-9}s^{-1} is about 0.7, which corresponds to the inverse value of OCR for the Osaka Pleistocene clays.

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REFERENCES

- 1) Den Haan, E. J. and Kamao, S. (2003): Obtaining isotache parameters from a C. R. S. Ko-Oedometer, *Soils and Foundations*, **43**(4), 203–214.
- 2) Imai, G. and Tan, Y. (1992): A constitutive equation of one-dimensional consolidation derived from inter-connected tests, *Soils and Foundations*, **32**(2), 83–96.
- 3) Itoh, Y., Takemura, K., Ishiyama, T., Tanaka, Y. and Iwaki, H. (2000): Basin formation at a contractional bend of a large trascurrent fault: Plio-Pleistocene subsidence of the Kobe and northern Osaka Basins, Japan, *Tectonophysics*, **321**, 327–341.
- 4) Leroueil, S. and Hight, D. (2003): Behaviour and properties of natural soils and soft rocks, *Characterization and Engineering Properties of Natural Soils*, Balkema Publishers, **1**, 29–254.
- 5) Leroueil, S., Kabbaj, M., Tavenas, F. and Bouchard, R. (1985): Stress-strain-strain rate relation for the compressibility of sensitive natural clays, *Geotechnique*, **35**, 159–180.
- 6) Nash, D. (2001): Modelling the effects of surcharge to reduce long term settlement of reclamations over soft clays: a numerical case history, *Soils and Foundations*, **41**(5), 1–13.
- 7) Tanaka, H. (2005a): Consolidation behavior of natural soils around p_c value—Long term consolidation test—, *Soils and Foundations*, **45**(3), 83–96.
- 8) Tanaka, H. (2005b): Consolidation behavior of natural soils around p_c value—Inter-connected oedometer test—, *Soils and Foundations*, **45**(3), 97–106.
- 9) Tanaka, H., Mishima, O. and Tanaka, M. (2000): The rate effect on p_c value for nine undisturbed marine clays, *Proc. 10th Int. Offshore and Polar Engineering Conf. (ISOPE)*, **2**, 649–652.
- 10) Tanaka, H., Ritoh, F. and Omukai, N. (2002): Quality of samples retrieved from great depth and its influence on consolidation properties, *Can. Geotech. J.*, **39**, 1288–1301.
- 11) Tanaka, H., Tanaka, M., Suzuki, S. and Sakagami, T. (2003): Development of a new cone penetrometer and its application to great depths of Pleistocene clays, *Soils and Foundations*, **43**(6), 51–61.
- 12) Tanaka, H., Kang, M. S. and Watabe, Y. (2004): Ageing effects on consolidation properties - Based on the site investigation of Osaka Pleistocene clays-, *Soils and Foundations*, **44**(6), 39–52.
- 13) Yoshikuni, H., Nishiumi, H., Ikegami, S. and Seto, K. (1994): The creep and effective stress-relation behavior on one-dimension consolidation, *Proc. 29th Jpn. Nat. Conf. SMFE.*, **29**, 269–270 (in Japanese).