Structure upgradation concept applied to cyclic mobility of sand and high ductility of natural clay

Mobilité cyclique du sable et haute ductilité des sols argileux naturels causées par un renforcement de la structure

K. Nakai, M. Nakano & A. Asaoka
Department of Civil Engineering, Nagoya University, Japan

T. Kawai
Central Research Institute of Electric Power Industry (CRIEPI)

ABSTRACT

The soil skeleton structure (structure, overconsolidation, and anisotropy) increases and decreases as the plastic deformation varies. Previously, only the structure has been considered to be degraded; however, observation of the undrained cyclic shear behavior of medium dense sand shows that not only does the structure degrade, but a structure upgradation process also occurs. Therefore, the concept of structure upgradation accompanying plastic swelling was introduced into the SYS Cam-clay model based on the results of testing. This structure upgradation concept makes it possible to describe the cyclic mobility of sand and to explain the high ductility behavior seen in soft natural clay.

RÉSUMÉ

L'augmentation des déformation plastiques va transformer voire disloquer la structure squelettique des sols (structure, surconsolidation, anisotropie). Il était considéré que l'affaiblissement des structures était uniforme mais l'observation du comportement en cisaillement non drainé des sables à densité moyenne montre l'existence d'un processus de renforcement de la structure en plus de son affaiblissement. Nous avons ainsi introduit le concept d'un renforcement de la structure dû à une expansion plastique dans le cadre du modèle SYS Cam-clay basé sur les résultats des expériences. La description de la mobilité cyclique des sables est la conséquence de ce concept de renforcement de la structure qui permet aussi d'expliquer la haute ductilité trouvée dans les sols argileux moux.

Keywords : structure upgradation, cyclic mobility of sand, high ductility of natural clay

1 INTRODUCTION

Through observations of the soil skeleton structure, including structure, overconsolidation and anisotropy, the present authors have proposed a new elasto-plastic constitutive equation, named SYS Cam-clay model (Asaoka et al. 2002). The proposed model accounts for the decay of structure, the loss of overconsolidation, and the appearance/disappearance of anisotropy accompanying the processes of plastic deformation of overconsolidated soil in a highly structured state. Figure 1 shows the results of standard consolidation test on undisturbed sample and thoroughly remolded sample. The undisturbed samples were taken carefully from a Joban clay layer observed to have delayed consolidation. Compared with the remolded sample, the undisturbed sample was bulky, with a large specific volume under the same amount of stress. When the "structure" is quantitatively defined by focusing on the bulky state, it can be seen that as the vertical stress increases, the undisturbed sample gradually loses their bulk, and the consolidation line for undisturbed samples asymptotically approaches the consolidation line of the remolded samples, so the structure is degraded by the consolidation process. This soil skeleton structure concept is not only applicable to clay, but also can be applied to sand. Loosely compacted sand with a high specific volume has a high degree of structure and a low overconsolidation ratio, and conversely, densely compacted sand with a low specific volume has a low degree structure and high overconsolidation ratio (Asaoka et al. 2002). The main results of research carried out to date indicate that (1) the difference between clay and sand can be described by the speed of evolution of the soil skeleton structure (the amount of change in the soil skeleton structure per unit of plastic deformation). Thus, when they are overconsolidated and highly structured, the degradation of structure is predominant over loss of overconsolidation in sand, and the loss of overconsolidation is predominant over degradation of structure in clay (Asaoka et al. 2002). Furthermore, (2) degradation of structure acts on plastic compression, so the rapid degradation of structure in sand causes liquefaction or compaction; however, the slow degradation of structure in clay causes it to experience large

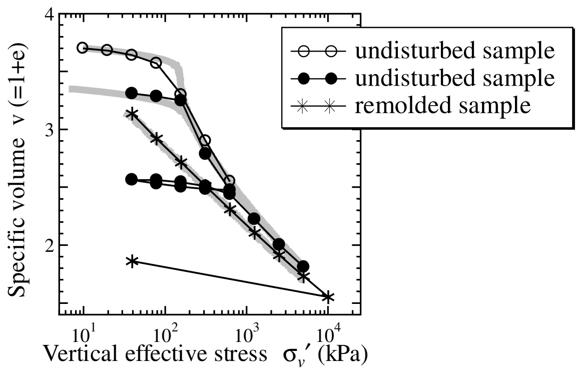

Figure 1. Standard consolidation test results

delayed compression (Asaoka et al. 2006).

Figures 2 and 3 are experimental comparisons that can be used as the foundation for a process of structure upgradation associated with shear as emphasized in this research. Undrained cyclic shear tests were carried out on medium dense sand with a uniform initial specific volume. Cyclic shear was stopped after different numbers of repetitions, and consolidated to initial stress. Then the samples were again subjected to undrained cyclic shear tests. In Fig.2, where the number of repetitions was small and there was almost no cyclic mobility history, the

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-175

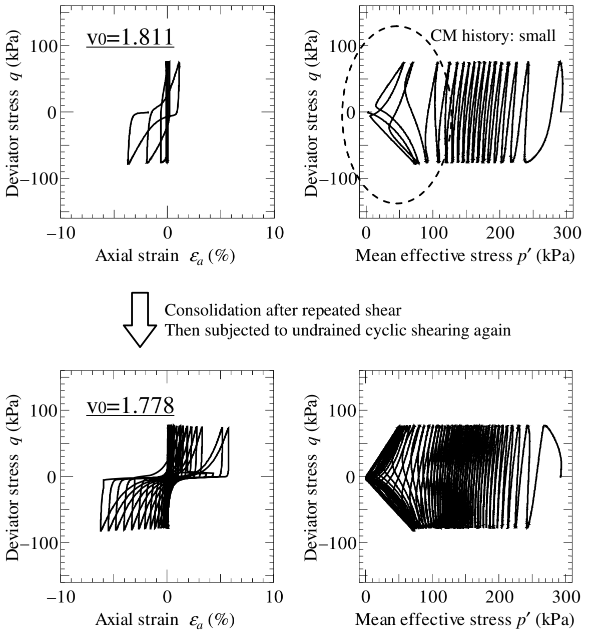

Figure 2. Increase in liquefaction strength seen after reconsolidation

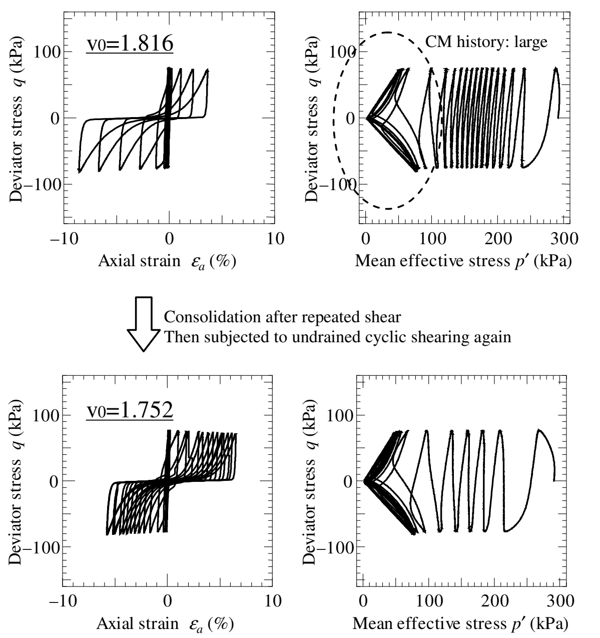

Figure 3. Reduction in liquefaction strength seen after reconsolidation

liquefaction strength increased due to the increase in density accompanying consolidation. On the other hand, in Fig.3, where the number of repetitions was larger and there was significant cyclic mobility history, although the density increased due to consolidation (although the compression was greater than in Fig.2), the reduction in p' was larger, and the liquefaction strength was reduced.

The speed of development of the soil skeleton structure, which characterizes the mechanical behavior of soils, is prescribed by evolution rules. However, the rules of structural evolution in the conventional elasto-plastic constitutive equation only consider the process of structural decay, as shown in Fig.1. However, liquefaction in which p' suddenly decreases under a low stress ratio due to shear is caused by structural degradation (Asaoka et al. 2002, 2006). Therefore, if an evolution rule like this is used, the following experimental facts cannot be explained: (1) reliquefaction of test samples that have previously been liquefied (once) and (2) reduction of liquefaction strength even though the density has increased. Therefore, it can be seen that the existence of structure upgradation as well as structure degradation is important for accurate description of the mechanical behavior of soils. In this paper, the concept of "structure upgradation associated with plastic swelling" is introduced into the structure evolution rule, and calculation examples are used to show that this concept is necessary not only for sand, but also for clay. In other words, this structure upgradation concept enables description of the cyclic mobility behavior of sand and the high ductility behavior (slow softening) seen in soft natural clay.

2 ESSENCE OF SYS CAM-CLAY MODEL AND INTRODUCTION OF STRUCTURE UPGRADATION CONCEPT

Naturally deposited soils, whether clay or sand, are generally in an overconsolidated state in which "structure" has developed. The normally consolidated state, thoroughly remolded with no structure, is the base for the elasto-plastic model expressing the mechanical behavior of highly structured overconsolidated soil. Anisotropy is also present in soil in the normal consolidation state, in which there is no structure, so in this paper, the stress parameter η^* (Sekiguchi & Ohta 1977) for expressing anisotropy, proposed by Sekiguchi and Ota, together with the rotational hardening concept (Hashiguchi & Chen 1998), which describes its evolution, are introduced into the modified Cam-clay model to form the starting point. The degree of structure is quantified by introducing the superloading surface concept (Asaoka et al. 2000), and the degree of overconsolidation is quantified by introducing the subloading surface (Hashiguchi 1978). In other words, the degree of structure is expressed by a superloading surface that is similar to the outside of the Cam-clay surface (the origin of the center of similitude is $p'=q=0$, and the similarity ratio is defined by R^* [$0<R^*\leq 1$]) (Asaoka et al. 2000), and the overconsolidation state is expressed by the subloading surface on the inside of the superloading surface (the origin of the center of similitude is $p'=q=0$, and the similarity ratio is defined by R [$0<R\leq 1$]; its inverse $1/R$ corresponds to the overconsolidation ratio) (Hashiguchi 1978, Asaoka et al. 1994). Here, p' is the mean effective stress, and q is the deviator stress. Therefore, using the effective stress $\boldsymbol{T}'$ (tension: positive), $p'=-\mathrm{tr}\boldsymbol{T}'/3$ and $q=\sqrt{3/2\,\boldsymbol{S}\cdot\boldsymbol{S}}$. As R^* approaches 0, the structure is upgraded, and as R^* approaches 1, the structure is degraded in association with plastic deformation (R^* evolution rule). Overconsolidation of the soil increases as R approaches 0, and as R approaches 1 due to the increase in plastic deformation, the soil approaches the normal consolidation state (R evolution rule). Therefore, as plastic deformation increases and the structure is degraded, the overconsolidation simultaneously dissipates (the normal consolidation state is approached), and the state ultimately coincides with that of the Cam-clay surface. The positional relationships of these three loading surfaces assuming axisymmetric conditions are shown in Figure 4. The current effective stress is on the subloading surface, so an associate flow rule, a consistency condition, and other elasto-plastic rules are applied to the subloading surface given by Equation (2), which is based on the Cam-clay yield surface give by Equation (1), for Cam-clay yield surface:

$$\begin{aligned}&\mathrm{MD}\ln\frac{\tilde{p}'}{\tilde{p}'_0}+\mathrm{MD}\ln\frac{\mathrm{M}^2+\eta^{*2}}{\mathrm{M}^2}+\int_0^t J\mathrm{tr}\boldsymbol{D}^p d\tau\\&\qquad=f(\tilde{p}',\eta^*)+\int_0^t J\mathrm{tr}\boldsymbol{D}^p d\tau=0\end{aligned}\qquad(1)$$

And, for subloading surface:

$$f(p',\eta^*)+\mathrm{MD}\ln R^*-\mathrm{MD}\ln R+\int_0^t J\mathrm{tr}\boldsymbol{D}^p d\tau=0\qquad(2)$$

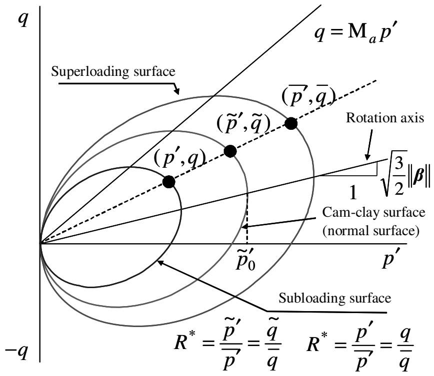

Figure 4. The three loading surfaces

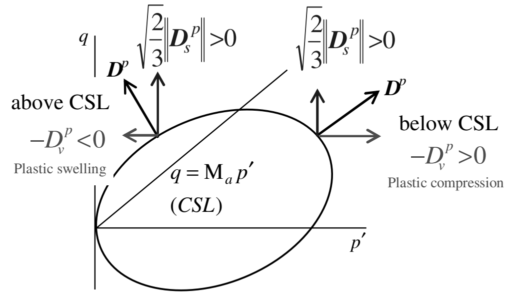

Figure 5. Sign of each component of plastic stretching

Here, $\mathrm{D} = (\tilde{\lambda} - \tilde{\kappa})/\mathrm{M}/(1+\mathrm{e}_0)$ is the dilatency coefficient; M, $\tilde{\lambda}$, $\tilde{\kappa}$, and e_0 are the critical state constant, compression index, swelling index, and initial void ratio; and $J = (1+\mathrm{e})/(1+\mathrm{e}_0)$, where e is the void ratio at time *t=t*. In the above equations, $-\int_0^t J\mathrm{tr}\boldsymbol{D}^p d\tau$ (compression: positive) corresponds to the plastic volumetric strain $\varepsilon_v{}^p$. Furthermore, η^* which expresses anisotropy, is expressed by the following equation using the effective stress, rotational hardening function $\boldsymbol{\beta}$, and other parameters.

$$\eta^* = \sqrt{3/2\,\hat{\boldsymbol{\eta}} \cdot \hat{\boldsymbol{\eta}}}\ ,\ \hat{\boldsymbol{\eta}} = \boldsymbol{\eta} - \boldsymbol{\beta}\ ,\ \boldsymbol{\eta} = \boldsymbol{S}/p'\ ,\ \boldsymbol{S} = \boldsymbol{T}' + p'\boldsymbol{I} \qquad (3)$$

From Equation (2), it can be seen that plastic compression ($\dot{\varepsilon}_v{}^p > 0$) is produced when the structure is degraded under load (R^* increases) and the overconsolidation is upgraded (R is reduced) and that plastic swelling ($\dot{\varepsilon}_v{}^p < 0$) is produced when the structure is upgraded (R^* is reduced) and overconsolidation is degraded (R increases).

The 3 evolution rules for skeleton structure (overconsolidation, anisotropy, and structure) are given by the following 3 equations.

$$\text{overconsolidation: } \dot{R} = JU\|\boldsymbol{D}^p\| \geq 0\ ,\ U = -\frac{m}{\mathrm{D}}\ln R \geq 0 \qquad (4)$$

$$\text{anisotropy} \quad : \overset{\circ}{\boldsymbol{\beta}} = J\frac{b_r}{\mathrm{D}}\sqrt{\frac{2}{3}}\|\boldsymbol{D}_s^p\|\|\hat{\boldsymbol{\eta}}\|\left(m_b\frac{\hat{\boldsymbol{\eta}}}{\|\hat{\boldsymbol{\eta}}\|} - \boldsymbol{\beta}\right) \qquad (5)$$

$$\text{structure} \quad : \dot{R}^* = JU^*\left\{c_s\sqrt{\frac{2}{3}}\|\boldsymbol{D}_s{}^p\| + (1-c_s)\left(-D_v{}^p\right)\right\},$$

$$U^* = \frac{a}{\mathrm{D}}R^{*b}(1-R^*)^c \geq 0 \qquad (6)$$

In Equation (5), $\overset{\circ}{\boldsymbol{\beta}}$ is the Green & Naghdi speed of $\boldsymbol{\beta}$ (Green & Naghdi 1965). The group of evolution rule parameters in Equations (4) through (6) is composed of constants, and based on their roles, *a*, *b*, and *c* are referred to as the evolution indices of structure; *m* is the evolution index of overconsolidation; b_r is the evolution index of anisotropy; and m_b is the limit of rotation. In the overconsolidation evolution rule, the plasticity measurement is given as the norma $\|\boldsymbol{D}^p\|$ of the plastic stretching $\boldsymbol{D}^p$, and the anisotropy is given as the deviatoric component $\|\boldsymbol{D}_s{}^p\|$ of $\boldsymbol{D}^p$. In the simplest structure evolution rule, $\|\boldsymbol{D}^p\|$ can be used as the plastic measurement, but in all cases of plastic deformation, $\dot{R}^* \geq 0$, so the structure only degrades. Therefore, to obtain an evolution rule that allows structure upgradation, the linear sum of the deviatoric component $\|\boldsymbol{D}_s{}^p\|$ of $\boldsymbol{D}^p$ and the volumetric component (isotropic component) $-D_v{}^p$ is introduced, as shown in Equation (6), and the ratio of the two is given by c_s ($0 \leq c_s \leq 1$).

In the SYS Cam-clay model, the slope M_s of the boundary line $q = \mathrm{M}_s p'$ between hardening and softening varies rapidly in accordance with the variations in the skeleton structure and the amount of stress that is present, and the slope M_a of the boundary line $q = \mathrm{M}_a p'$ between plastic compression and swelling increases and decreases in accordance with the development or loss of anisotropy. Based on Figure 5, the deviatoric component $\|\boldsymbol{D}_s{}^p\|$ term in Equation (6) (the first term on the right side) is always positive, regardless of whether there is plastic compression or plastic swelling, so the structure degrades. However, the term for the volumetric component $-D_v{}^p$ (the second term from the right side) becomes negative during plastic swelling, so the structure degradation is reduced. Furthermore, when the negative effect of $-D_v{}^p$ predominates over the $\|\boldsymbol{D}_s{}^p\|$ term, $\dot{R}^* < 0$, and structure upgradation occurs.

3 REPRODUCTION OF THE CYCLIC MOBILITY BEHAVIOR OF SAND

Figure 6 shows the results of calculation of the undrained cyclic shear behavior according to the evolution rule to which the structure upgradation concept was introduced (Equation [6]). In order for the shape of the yield surface to become flat and the elastic area (unloaded area) under low confining stress to become smaller as the anisotropy evolves, M^2 in the yield function (Equation [1]) is replaced with $\mathrm{M}^2\exp(-\varsigma^2)$ and the evolution rules for overconsolidation and anisotropy are slightly modified (Noda & Nakai 2009). The ratio c_s of the volumetric component $-D_v{}^p$ and deviatoric component $\|\boldsymbol{D}_s{}^p\|$ of the plastic stretching was set in the range of $0 \leq c_s \leq 1$ based on experimental results using the following equation so that, under

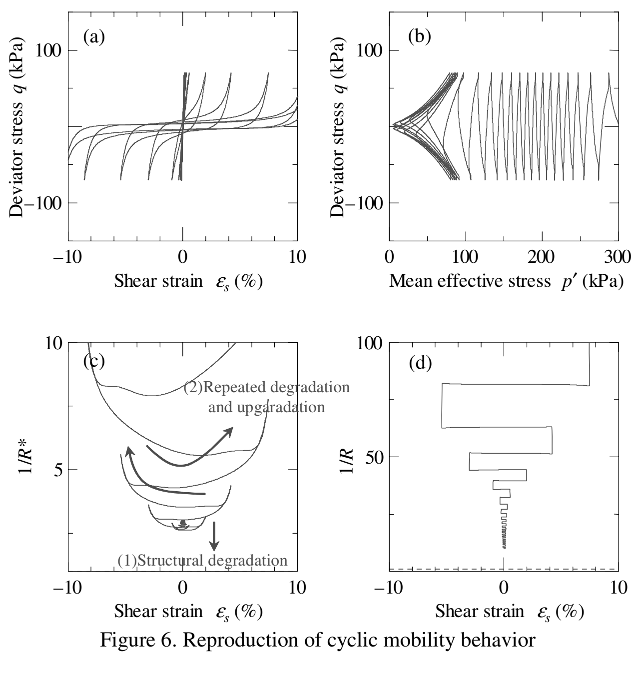

Figure 6. Reproduction of cyclic mobility behavior

high confining pressure, $\|D_s{}^p\|$ is dominant and the structure always degrades, and under low confining pressure, $-D_v{}^p$ is dominant and structure upgradation occurs during plastic swelling.

$$c_s = \exp\left\{-c_a\left(p'/p'_r\right)^2\right\} \quad (p'_r : reference\ stress) \tag{7}$$

The cyclic mobility characteristics, such as (1) p' reducing to zero and (2) the stress strain curve being concave upwards (stiffness increases), were reproduced well. Based on Fig. 7(c), the structure, which has been degraded (reduction in $1/R^*$) under high confining pressure, gradually accumulates through repeated upgradation when plastic swelling occurs and degradation when plastic compression occurs during cyclic mobility under low confining pressure.

4 REPRODUCTION OF THE HIGH DUCTILITY BEHAVIOR OF STRUCTURED NATURAL CLAY

Figure 7 shows the results for undrained shear tests using the same kind of undisturbed Joban clay sample as in Fig.1, but with a different degree of consolidation stress. Fig.7(c) shows both the remolded normal consolidation (NCL) and the critical state lines (CSL) obtained by reference to the one-dimensional compression curve of the remolded samples in Fig.1. When subjected to shear, softening behavior can be seen after hardening under low confining pressure (recovery behavior) and can be seen under high confining pressure; this is characteristic of the behavior of natural clay with a high degree of structure. However, as shown in Fig.7(c), even when 10% shear deformation is applied, the stress condition is above the NCL in all cases, so the structure upgradation does not sufficiently advance. On the other hand, as can be seen in Fig.1, the structure is easily degraded to virtually the remolded state in one-dimensional compression tests. It can be seen that one of the characteristics of the structure of Joban clay is that "degradation under compression (when $\|D_s{}^p\|$ is predominant over $-D_v{}^p$) occurs easily under low stress ratios, but does not occur easily under shear (when $-D_v{}^p$ is predominant over $\|D_s{}^p\|$), even for stress ratios approaching the critical state (softening is slow)." In Figs.1 and 7, the calculation results for the evolution rules to which the structure upgradation concept was introduced (Equation [6]) are shown using solid lines (light color); for cases in which the structure upgradation concept was not introduced ($\|D^p\|$ used for the plasticity measurement), the calculation results are shown using dotted lines (light color).

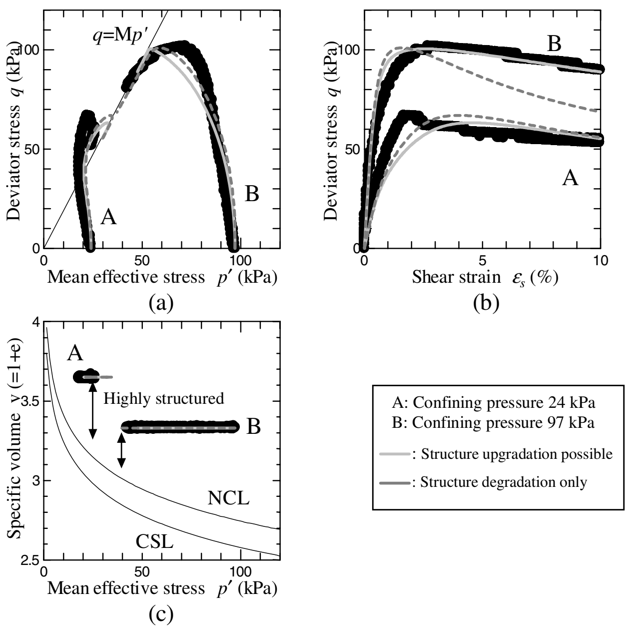

Figure 7. Reproduction of the high ductility behavior seen in soft clay

Common constants were used in the standard consolidation tests and undrained shear tests. When the structure upgradation concept was not introduced, severe structure degradation occurred during shear behavior, and excessive softening behavior occurred after hardening. However, when the structure upgradation concept was introduced, the calculations were capable of very finely reproducing both the compression and shear behaviors. Based on the test results, the value of c_s, the ratio of the volumetric component $-D_v{}^p$ to the deviatoric component $\|D_s{}^p\|$ of plastic stretching, was set to 0.2 in order to make the structure degradation due to compression predominant over shear. However, the effect of the change in structure as a proportion of $\|D_s{}^p\|$ was smaller than $-D_v{}^p$, so structure degradation was slow close to the critical state ($-D_v{}^p = 0$), and the degree of softening was reduced.

5 CONCLUSION

The structure upgradation process was clarified based on the results of undrained cyclic shear tests for medium dense sand using triaxial testing apparatuses. Based on the results, it was possible to model structure upgradation by applying the linear sum of the volumetric component $-D_v{}^p$ and deviatoric component $\|D_s{}^p\|$ of plastic stretching to the plasticity measurement of the evolution rule for structure in the SYS Cam-clay model. As a result, it is possible to not only describe the cyclic mobility behavior of sand, but also to describe the characteristic structure degradation of highly structured clay (high ductility in which degradation under compression occurs easily under low stress ratios, but does not occur easily under shear for stress ratios approaching the critical state). The present study has also shown that structure upgradation is important, for both sand and clay, during plastic swelling. We believe that introduction of the concept of structure upgradation makes it possible to simulate the phenomenon of reliquefaction of soils that have previously been liquefied (once) within a boundary value problem.

REFERENCES

Asaoka, A., Nakano, M. & Noda, T. 1994. Soil-water coupled behaviour of saturated clay near/at critical state, *Soils and Foundations*, **34** (1): 91-106.

Asaoka, A., Nakano, M. & Noda, T. 2000. Superloading yield surface concept for highly structured soil behavior, *Soils and Foundations*, **40**(2): 99-110.

Asaoka, A., Noda, T., Yamada, E., Kaneda, K. & Nakano, M. 2002. An elasto-plastic description of two distinct volume change mechanisms of soils, *Soils and Foundations*, **42**(5): 47-57.

Asaoka, A., Nakano, M. & Noda, T. 2006. A super/subloading yield surface approach to compaction/liquefaction of sand and secondary consolidation of clay, *2nd Japan-U.S. Workshop on Testing, Modeling and Simulation in Geomechanics*: 201-218.

Green, A.E. & Naghdi, P. M. 1965. A general theory of an elastic-plastic continuum, *Arch. Rat. Mech. and Analy* 18: 251-281.

Hashiguchi, K. 1978. Plastic constitutive equations of granular materials, Cowin, S.C. & Satake, M. (eds), *Proc. of US-Japan Seminar on Continuum Mechanics and Statistical Approaches in the Mechanics of Granular Materials*: 321-329. Sendai.

Hashiguchi, K. & Chen, Z.-P. 1998. Elastoplastic constitutive equations of soils with the subloading surface and the rotational hardening, *Int. J. Numer. Anal. Meth. Geomech.*, **22**: 197-227.

Noda, T. & Nakai, K. 2009. Explanation of cyclic mobility of sand, approach by re-upgradation of the soil skeleton structure, *Soils & Foundations*, under contribution.

Sekiguchi, H. & Ohta H. 1977. Induced anisotropy and time dependency in clays, *Constitutive Equations of Soils (Proc. 9th Int. Conf. Soil Mech. Found. Eng., Spec. Session 9)*: 229-238. Tokyo.