Technol Rep Yamaguchi Univ 5(1) : 11-21, 1992

Deformation Characteristics of Sand Subjected to Drained Cyclic Loading

Yukio NAKATA*, Hidekazu MURATA**, Noriyuki YASUFUKU**,
Masayuki HYODO** and Akihiro NISHIKAWA*

(Received August 5, 1992)

Abstract

The aim of the present study is to investigate the deformation characteristics of sand subjected to drained cyclic loading. The following major conclusions have been obtained: (1) The stress-dilatancy relationship is recognized to have no effect of the confining pressure in spite of the number of cycles. (2) Although the volumetric strain accumulated for first loading decreases with the increasing over consolidation ratio (OCR), the influence seems to be disappeared with the increasing number of cycles. (3) The anisotropically consolidated sample occurs the volumetric strain larger than the isotropically consolidated one, especially during first unloading.

Introduction

The liquefaction and flow deformation of sand ground have induced by earthquake, wave loading, traffic loading and so on. As a result, the great disaster has often occurred. The stress induced by such external forces as mentioned above are generally treated as the cyclic loading. Many researchers have carried out the experimental and analytical study to make clear the behaviour of sand under cyclic loading conditions (e.g. Ishihara, Tatsuoka and Yasuda[1], Hyodo, Murata, Yasufuku and Fujii[2] among others). However, there are many points which must be clarified as to the behaviour.

The above experimental study has been mainly performed under undrained conditions. The authors have considered that the cyclic triaxial test need to be also performed under drained conditions in order to understand the essential points about the deformation characteristics and to develop the constitutive equation for sand under cyclic loading condition. The study as to the drained cyclic behaviour of sand has been practiced by Tatsuoka and Ishihara[3], Yagi[4], Matsuoka and Geka[5], Nemat-nasser and Takahashi[6], Pradhan, Tatsuoka and Sato[7], Nishi and Kanatani[8] and so on. Such studies have been carried out for isotropically consolidated sand. Considering the facts that in-situ stress state of soils are generally anisotropic and the stress conditions tend to have major effects on the deformation behaviour, the deformation

*Graduate student, Department of Civil Engineering
**Department of Civil Engineering

characteristics for anisotropically consolidated sand under drained cyclic loading should be also examined in detail.

In the present study, the experimental study under axial symmetric conditions are carried out to investigate the deformation characteristics of sand subjected to drained cyclic loading with particular reference to the consolidated history. A series of the drained cyclic triaxial tests are first performed for isotropically consolidated sand. Moreover, the drained cyclic loading tests are carried out for anisotropically consolidated sand. The effect of the consolidated history and the number of drained cyclic loadings on the stress-strain and stress-dilatancy relationships will be discussed on the basis of the experimental results obtained.

Specimen Preparation

The sample used in this study was "Aio" sand. The index properties are as follows: $G_s=2.63$, $U_c=2.74$, $D_{50}=0.41$, $e_{max}=0.96$ and $e_{min}=0.58$. Specimens were prepared for drained cyclic test by pluviating air dried particles through air. Then, carbon deoxide gas and de-aired water were percolated through the specimens. A back pressure of 2.0kgf/cm² was applied to all the specimens. A fully saturated specimen with relative density $D_r=55\pm5\%$ (initial void ratio $e_i=0.73$-0.77) was formed, 50mm in diameter and 100mm in height.

The triaxial tests were carried out using a stress-controled triaxial apparatus. All the triaxial tests were performed under drained conditions. The correction of the measured volume change due to membrane penetration was made using the method developed by Vaid and Negussey[8].

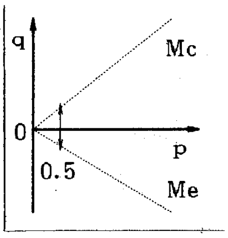
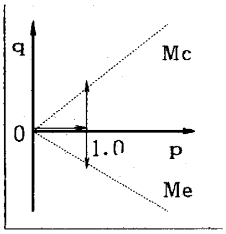
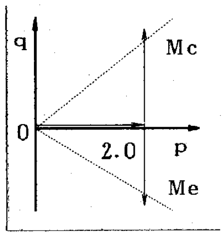
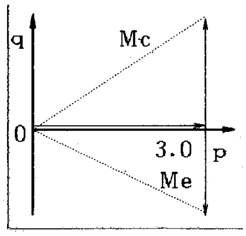
In this study, the following stress and strain parameters were used: $p=(\sigma_a+2\sigma_r)/3$, $q=\sigma_a-\sigma_r$, $\eta=q/p$, $v=\varepsilon_a+2\varepsilon_r$, $\varepsilon=2(\varepsilon_a-\varepsilon_r)/3$ and $\psi^p=-dv/d\varepsilon^p$, where p is the mean principal effective stress; q is the deviator stress and η is the stress ratio; σ_a and σ_r are the axial and radial effective stresses, respectively; v is the volumetric strain, ε is the shear strain and ψ^p is the plastic strain increment ratio; ε_a and ε_r are the axial and radial strains, respectively; dv and $d\varepsilon^p$ are the increment of the volumetric and plastic shear strain, respectively. The compressive stresses and strains are taken as positive.

Drained Cyclic Test Path

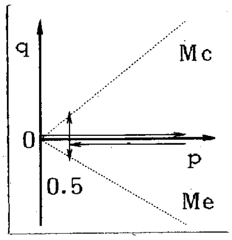
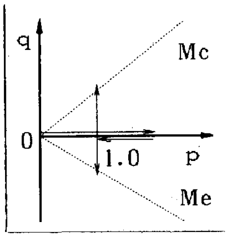
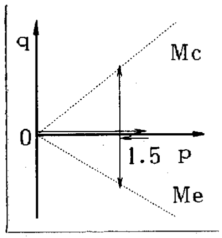
In this paper, a series of drained triaxial tests under cyclic loading conditions were carried out in order to invesitigate the effect of confining pressure, over consolidated history and consolidated path on the stress-strain and stress-dilatancy relationships. A list of cyclic loading tests performed in this study is described in Table 1. Table 1 (a) shows the stress paths to investigate the effects of confining pressure from 0.5 to 3.0kgf/cm² on the deformation characteristics of sand, (b) shows the paths to define the effects of over consolidated history, and (c) shows the paths to investigate the dependency of consolidated path, in which all tests were performed under constant p condition and the stress amplitude in the range of $\eta=1.25\sim-0.825$ to the specimens. In order to illustrate the uniformity of the specimens, the initial void ratio e_i and void ratio e_0 after consolidation are described in Table 1. In this table, M_c and M_e are

Table 1 List of drained cyclic tests

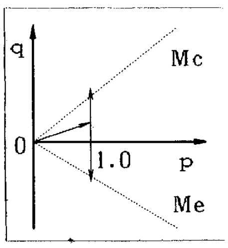
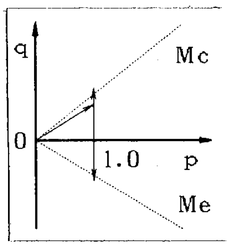
(a) Effect of confining pressure level

path				
e_i	0.750	0.759	0.751	0.751
e_o	0.748	0.754	0.741	0,738

(b) Effect of over consolidated history

Path			
e_i	0,738	0.738	0.760
e_o	0.731	0,730	0,750

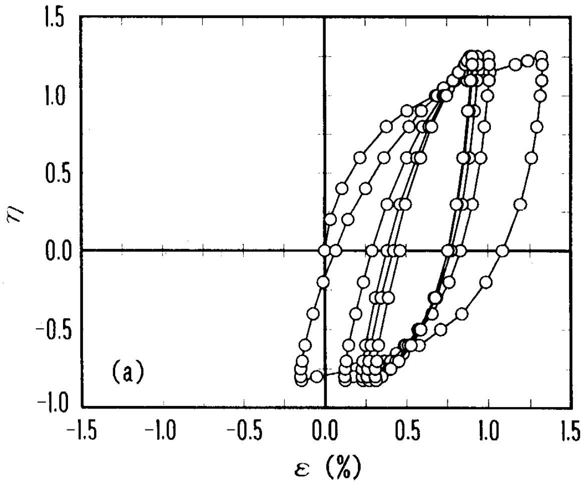
(c) Effect of consolidaton path

path		
e_i	0,762	0,736
e_o	0.752	0,730

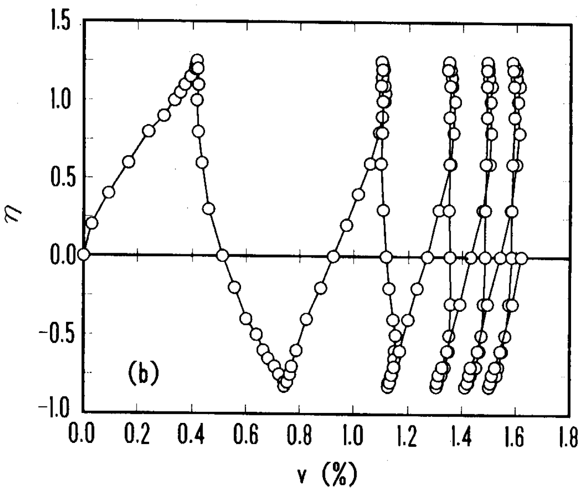
stress ratio η at dv=0 in compression and extention side, the lines in p-q space which defined by M_c and/or M_e are called the phase transformation line. M_c and M_e were given as 1.2 and -0.9 for Aio sand used (Dr=55%).

Test Results

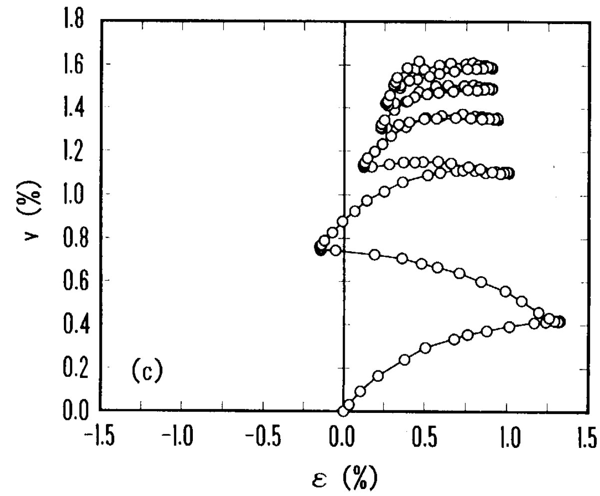
Fig. 1(a) to (e) show the results of drained cyclic test performed at p=2.0kgf/cm²



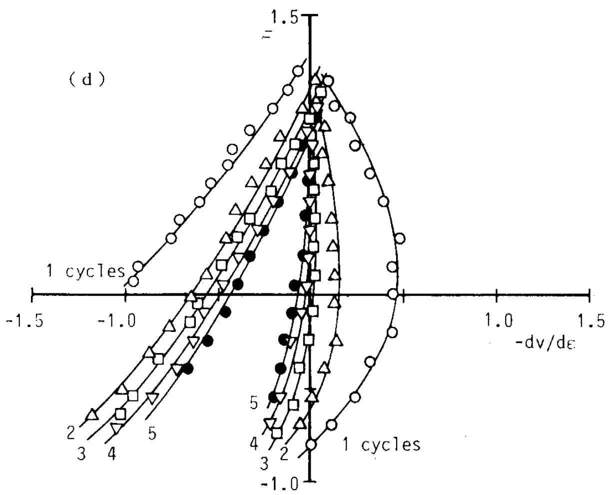
(a) η-ε relationship



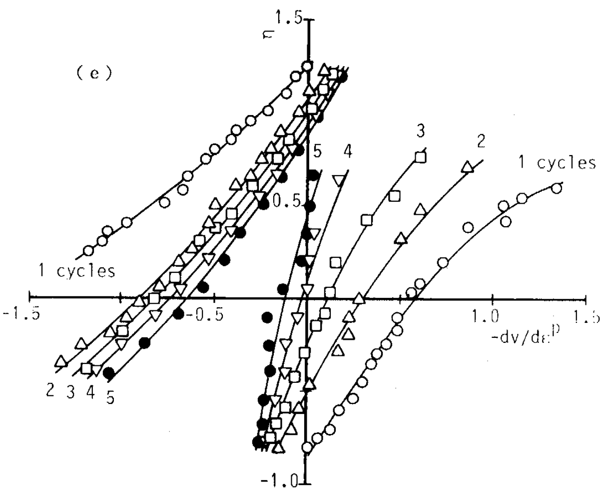
(b) η-v relationship



(c) v-ε relationship



(d) η-(-dv/dε) relationship



(e) η-(-dv/dε^p) relationship

Fig. 1 Typical results of drained triaxial cyclic test ($p=2.0\text{kgf/cm}^2$ and OCR=1) and OCR=1.0. Here, OCR means the over consolidation ratio which defined by p_c/p_o in which p_c and p_o are preconsolidation pressure and consolidation pressure before drained cyclic loading. The η-ε and η-v relationship is shown in Fig. 1(a) and (b). The strain path in terms of v and ε is illustrated in Fig. 1(c). Since these tests were performed at constant p condition, the volumetric strain can be considered to the dilatancy due to shear. In these figures, it can be observed that (1) the amplitude of shear strain decreases with the increasing number of cycles and (2) the volumetric strain is compressibly accumulated with the increasing number of cycles. Each accumulated volumetric strain is 0.9%, 1.3%, 1.5%, 1.65% and 1.75%, respectively. In fact, it is found that the increment of the accumulated volumetric strain at each cycle decreases with the increasing number of cyclic loading. In Fig. 1(b), the stress ratio M_c as phase transformation stage are shown with the arrow. It should be noticed that M_c decreases with the increasing number of cycles.

Fig. 1(d) shows the relationship between stress ratio and strain increment ratio ($-dv/d\varepsilon$). The strain increment ratio means the slope of tangent in strain path (see Fig. 1(c)). In general, it is considered that $d\varepsilon$ consists of the elastic component ($d\varepsilon^e$) and the plastic component ($d\varepsilon^p$) of shear strain. Therefore, the plastic component ($d\varepsilon^p$) was evaluated by using shear elastic modulus G which is defined by initial secant slope of the q-ε relationship. The G value was evaluated by the following equations:

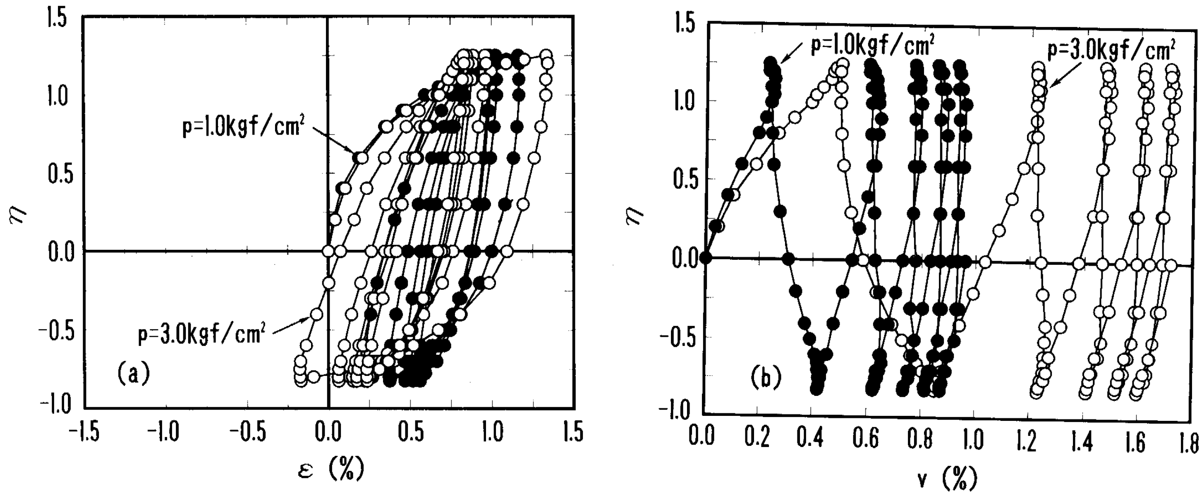
$$d\varepsilon^e = \frac{1}{3G} dq : \qquad G = a\left(\frac{p}{p_a}\right)^b \tag{1}$$

where p_a is the unit pressure and "a" and "b" for Aio sand used are 397kgf/cm² and 0.4, respectively. Using Eq.(1), as a result, the relationships between stress ratio and plastic strain increment ratio ψ^p is shown in Fig. 1(e). This relationship is often called the stress-dilatancy relationship. It is indicated that the slope and the intercept of the stress-dilatancy line change with the increasing number of cycles. The similar result has been indicated by Nemat-nasser and Takahashi[5], Pradhan, Tatsuoka and Sato[6] and Nishi and Kanatani[7] using by the conventional triaxial, simple shear and hollow cylindrical torsional apparatus.

Effect of Confining Pressure

Fig. 2(a) and (b) show the stress-strain relationships in the cyclic loading test performed at p=1.0 and 3.0kgf/cm². The η-ε and η-v relationship are shown in Fig. 2(a) and (b), respectively. In these figures, it is found that the amount of shear and volumetric strain accumulated at each cycle decreases gradually with the increasing number of cycles, depending on the confining pressure.

The stress ratio-plastic strain increment ratio relationship corresponding to first and fifth cycle are shown in Fig. 3(a) and (b), respectively. These figures show the cyclic test result performed at p=0.5, 1.0, 2.0 and 3.0kgf/cm². The stress-dilatancy relationship is recognized to have no effect of the confining pressure in spite of the number of cycles, namely, when the number of cycles is determined, the η-ψ^p relationship can be uniquely given irrespective of the confining pressure. Further, it is also



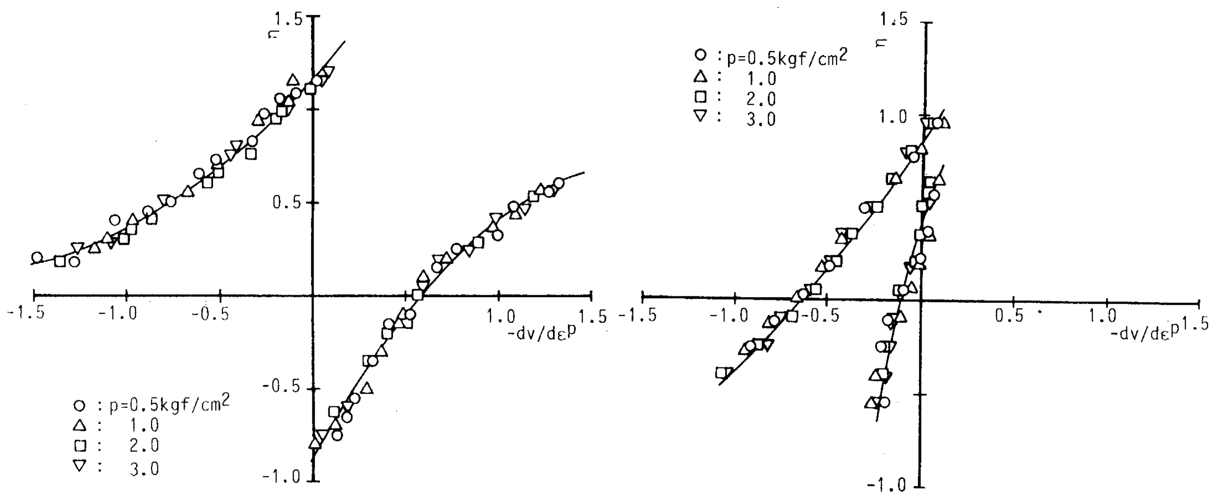
(a) η-ε curves (b) η-v curves

Fig. 2 Effect of confining pressure on the stress-strain curve

recognized that the slope of the η-ψ^{p} relationship increases with the increasing number of cycles.

Effect of Over Consolidation

Fig. 4 shows the η-v relationship in the cyclic loading test performed at p=1.0 kgf/cm². This figure compares the η-v relationship for normally consolidated (NC) sample with that for over consolidated (OC) sample (OCR=2.0). The over consolidation consists of the loading along η=0.0 until p=2.0kgf/cm² and the unloading until p=1.0kgf/cm². The drained cyclic loading tests for the NC and OC sample were then carried out at constant p condition. In this figure, it is observed that especially at the



(a) first cycle (b) fifth cycle

Fig. 3 Effect of confining pressure on stress-dilatancy relationship first loading, there is significant difference between NC and OC sample on the η-v relationship. In order to make more clear the behaviour described above, the η-v relationship is rearranged. Fig. 5 shows the η-v relationship, in which v is written zero to replace the volumetric strain at peak stress ratio in Fig. 4. The result of first and second cycle are shown in Fig. 5(a) and (b), respectively. When the stress ratio is equal to M_C at first loading, the difference between NC and OC sample is about 0.2%. There is, however, almost no significant difference between NC and OC sample at the first unloading and second loading. Here, the loading means $d\eta$ is positive and the unloading means $d\eta$ is negative, respectively. This behaviour indicates that although in the case of OCR=2.0, the influence of the over consolidated history exists for the first loading, the influence seems to be disappeared after first unloading.

Moreover, the comparison between the η-v relationship for normally consolidated

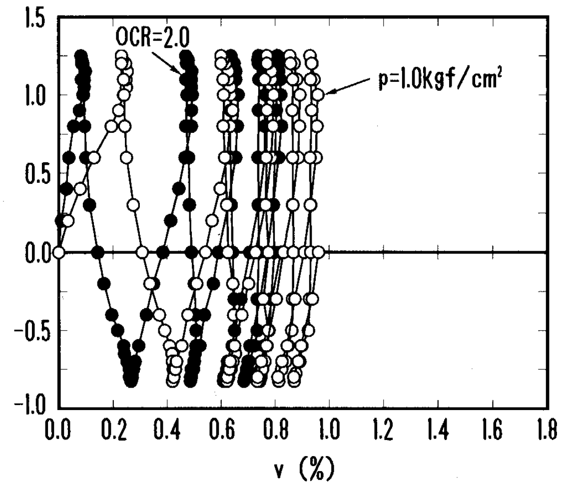
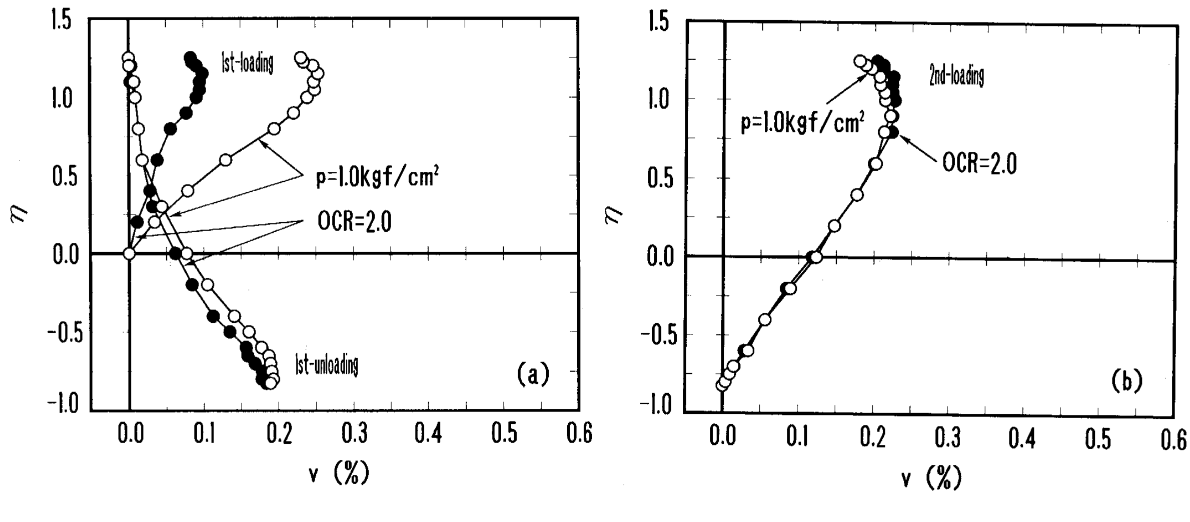
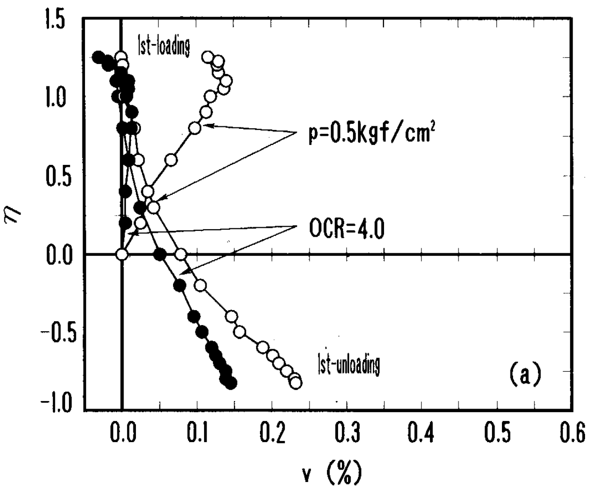


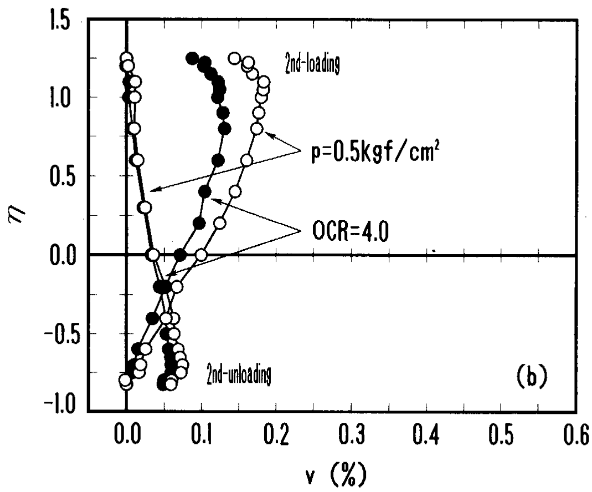
Fig. 4 Effect of over consolidated history on the η-v curves



(a) first cycle (b) second cycle

Fig. 5 Comparison of η-v curves for normally and lightly over consolidated sample





(a) first cycle (b) second cycle

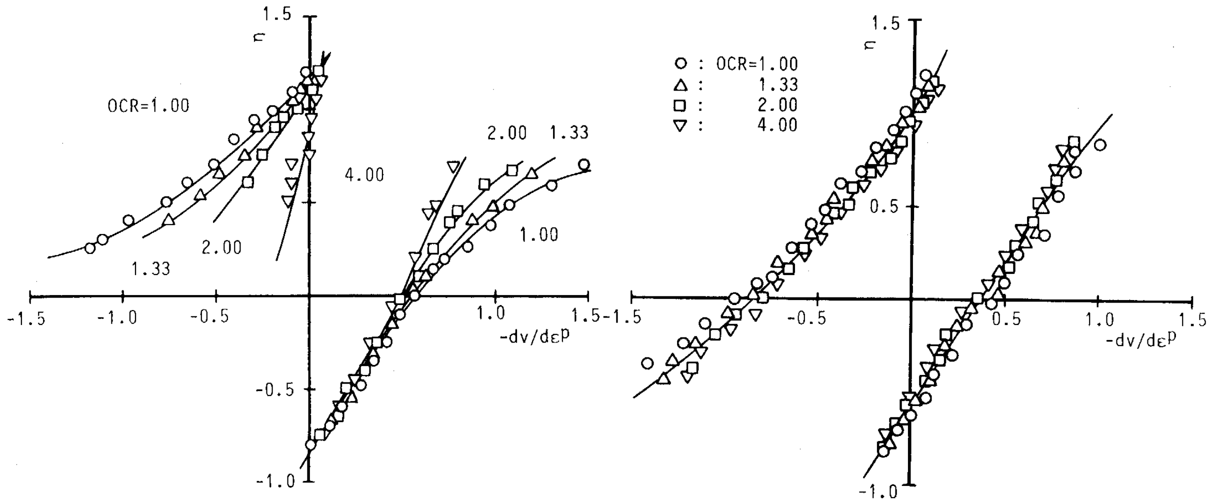
Fig. 6 Comparison of η-v curves for normally and heavily over consolidated sample

(NC) sample with that for heavily over consolidated (OC) (OCR=4.0) is illustrated in Fig. 6, which is depicted by the same manner as Fig. 5. Each test was performed at p=0.5kgf/cm². Fig. 6(a) and (b) show the result of first and second cycle, respectively. When the magnitude of stress ratio reaches the magnitude of M, the difference of v for each sample is approximately 0.15% at first loading, 0.1% at first unloading and 0.05% at second loading. It, however, is obtained that the η-v relationship at second unloading coincides with each sample. It implies that the sample gradually loses the effect of over consolidated history during cyclic loading. This interesting behaviour should be regarded as one of important deformation characteristics of sand.

Fig. 7(a) and (b) are prepared to evaluate the effect of over consolidated history on the stress-dailatancy relationships. The effect of the number of cyclic can be also evaluated in these figures, as Fig. 7(a) and (b) indicate first and second cycles, respectively. It is found that the ψ^p at the first loading increases with the increasing over consolidation ratio and the ψ^p at the initial part of first unloading decreases with the increasing over consolidation ratio. It, however, can be seen that there is no effect of over consolidated history on the η-ψ^p relationship at second cycle. These results can be considered to be valid, because it has been obtained that the effect of over consolidated history disappears slowly on the η-v relationship as shown in Figs. 5 and 6.

Effect of Consolidation Path

Fig. 8 illustrates the η-v relationship of the test result in case of stress ratio $\eta=0.0$ and 1.2 at the consolidation. The sample corresponding to $\eta=1.2$ was consolidated



(a) first cycle (b) second cycle

Fig. 7 Effect of over consolidated history on stress-dilatancy relationship

anisotropically until p=1.0kgf/cm² along $\eta=1.2$. It is shown in Fig. 8 that especially during first unloading, the anisotropically consolidated sample occurs the volumetric strain larger than the isotropically consolidated one. In order to clarify the above behaviour, the η-v relationship during first unloading is illustrated in Fig. 9, which is rearranged in the same manner as Fig. 5. The result of sample consolidated at $\eta=0.6$ is also indicated in this figure. In Fig. 9, the volumetric strain corresponding to $\eta=$ 0.0, 0.6 and 1.2 yeild 0.2, 0.3 and 0.4% during first loading, respectively. The difference can be caused by the anisotropy induced during the consolidation.

The η-ψ^p relationship is shown in Fig. 10 to understand the effect of consolidation path. The results of first and second cycle are shown in Fig. 10(a) and (b). It is indicated in Fig. 10(a) that the η-ψ^p curves locate upper with the increase of stress ratio during consolidation. However, the η-ψ^p relationship for second cycle in Fig. 10(b) can be drawn by a unique curve, irrespective of consolidated paths. This reason

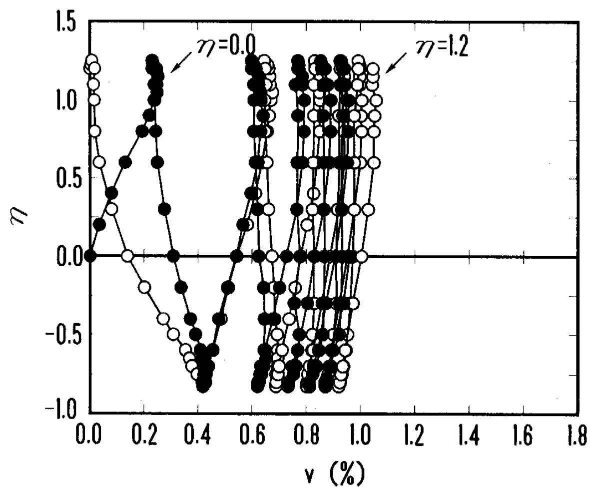


Fig. 8 Effect of consolidated path on the η-v curves

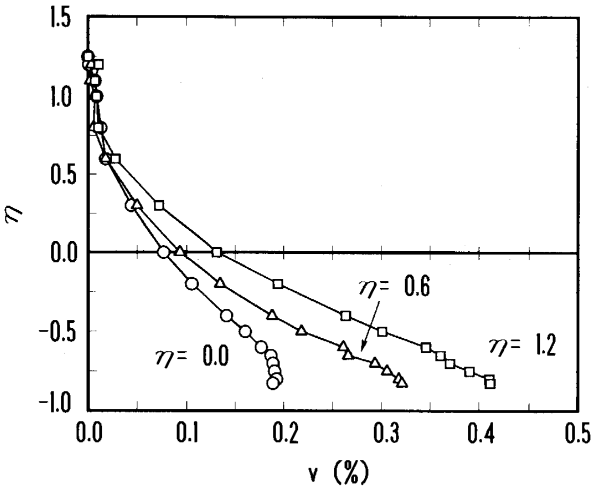
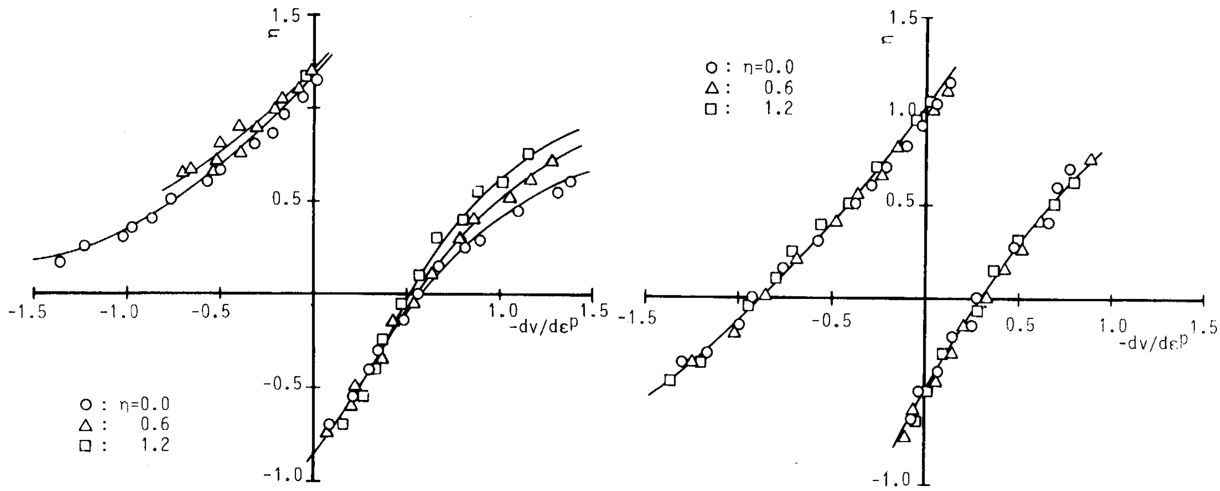


Fig. 9 Effect of consolidated path on the η-v curves during first unloading



(a) first cycle (b) second cycle

Fig.10 Effect of consolidated path on stress-dilatancy relationship

seems to be that the anisotropy induced by the consolidated path is gradually disappeared during drained cyclic loading as well as the effect of over consolidated history.

Conclusions

In this paper, a series of drained triaxial tests under cyclic loading conditions were carried out in order to investigate the effect of confining pressure, over consolidated history and consolidated path on the stress-strain and stress-dilatancy relatonships. The major conclusions are the followings:

(1) The amount of shear and volumetric strain accumulated at each loading cycle decreases gradually with the increasing number of cycles, depending on the

confining pressure.

(2) The stress-dilatancy relationship is recognized to have no effect of the confining pressre in spite of the number of cycles.

(3) Although the volumetric strain accumulated for first loading decreases with the increasing over consolidation ratio (OCR), the influence seems to be disappeared with the increasing number of cycles.

(4) The plastic strain increment ratio (ψ^p) at the first loading increases with the increasing OCR and the ψ^p at the initial part of first unloading decreases with the increasing OCR. It, however, can be seen that there is no effect of over consolidated history on the η-ψ^p relationship at second cycle.

(5) The anisotropically consolidated sample occurs the volumetric strain larger than the isotropically consolidated one, especially during first unloading.

(6) Although the η-ψ^p curves for first cycle locate upper with the increasing of stress ratio during consolidation, the η-ψ^p relationship for second cycle can be drawn by a unique curve, irrespective of consolidated paths.

References

1) Ishihara, K., Tatsuoka, F and Yasuda, S (1975) :"Undrained deformation and liquefaction of sand under cyclic stresses," Soils and Foundations, Vol.15, No.1, pp.29-44.

2) Hyodo, M., Murata, H., Yasufuku, N. and Fujii T. (1991) :"Undrained cyclic shear strength and residual shear strain of saturated sand by cyclic triaxial tests," Soils and Foundations, Vol.31, No. 3, pp.60-76.

3) Tatsuoka, F and Ishihara, K. (1974) :"Drained deformation of sand under cyclic stresses reversing direction," Soils and Foundations, Vol.14, No.3, pp.51-65.

4) Yagi, N., (1978):"Volume change and excess pore pressure of sand due to cyclic shear," Proceedings of Vol.275, pp.79-90.(in Japanese)

5) Matsuoka, H. and Geka, H. (1983):"A stress-strain model for granular materials considering mechanism of fabric change," Soils and Foundations, No.2, Vol.2, pp.83-97.

6) Nemat-Nasser, S. and Takahashi, K.(1984) :"Liquefaction and fabric of sand," Journal of Geotechnical engineering, Vol.110, No.9, pp. 1291-1306.

7) Pradhan, T.B.S, Tatsuoka, F. and Sato, Y. (1989) : " Experimental stress-dilatancy relations of sand subjected to cyclic loading," Soils and Foundation, Vol.29, No.1, pp.45-64.

8) Nishi, K. and Kanatani, M. (1990) :" Constitutive relations for sand under cyclic loading based on elasto-plasticity theory," Soils and Foundations, Vol.30, No.2, pp.43-59.

9) Vaid, Y. P. and Negussey, D. (1984): " A critical assessment of membrane penetration effects in drained tests," Geotechnical Testing Journal,Vol.7, No.2, pp.70-76.