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Synopsis: In this study, the yield locus of sand being subjected to several cycles of undrained loading was investigated by using the triaxial testing device capable of measuring the acoustic emission, AE, of soil. The AE measurement indicates that the undrained shear on isotropically consolidated sand changes the shape of yield locus so as to have more kinematic hardening type of yield locus. More importantly, a change occurred in the size of yield locus, and the undrained loading has reduced the size of yield locus. Subsequent undrained cyclic loadings further reduced the size of yield locus so that there were some additional yielding during the cyclic loadings which accompanied gradual accumulations of pore water pressures.

INTRODUCTION

Recently, much advances have been made on the numerical modelling of soil to simulate the phenomenon of sand liquefaction, and the modelling is made usually by employing the elasto-plastic type soil models. However, some tactical assumptions seem to be needed for these soil models to predict practically the accumuiation of pore water pressure during undrained cyclic loading, for example some recent soil models incorporate some yielding behavior within the elastic yielding stress region to simulate the accumulation of pore water pressure, for example Prevost (1986) and Norris (1986). Although Ishihara and Okada (1978) have made some study on this aspect of soil behavior, experimental results are very limited. Therefore some uncertainty still seems to exist on how to define the boundary between the elastic behavior and the plastic behavior of actual soil during undrained cyclic loading.

This paper is concerned with the experimental study on the yielding behavior of sand during undrained cyclic loading. The difficulty of defining the yield stress in the standard procedure of soil testing, i.e., basing on the stress-strain relationship, is reduced by the use of acoustic emission, AE, measurement during the test. The technique of acoustic emission measurement is widely used in the study of metal or rock materials to define the yield stress under uniaxial loading. Past study of AE in soil mechanic field has shown that the AE measurement is also useful in determining the yield stress of sand, for example Tanimoto and Tanaka (1986). It is found that the sand with isotropic pre-stressing has a elastic region (yield locus) as defined in the three dimensional stress space, and loading below the yield stress results in minimal deformation response of soil. The yielding behaviour of anisotropically consolidated sand was also studied by using AE, Tanimoto et al. (1987), and it was found that the yield locus of anisotropically consolidated sand has a kinematic hardening type of yield locus. Thus in this paper the AE technique was used to define the yield locus of sand during undrained loading and also to study the change of yield locus after subjecting the sand to undrained cyclic loadings.

TEST APPARATUS AND METHOD

In this study, a triaxial test apparatus capable of measuring the Acoustic Emission (AE) of soil was used. The details of this test apparatus has been described elsewhere, for example Tanaka and Shirakawa (1993), and therefore only a brief description of the apparatus is given here. Figure 1 shows the outline of triaxial testing system used to measure AE of sand during undrained cyclic loading. The size of

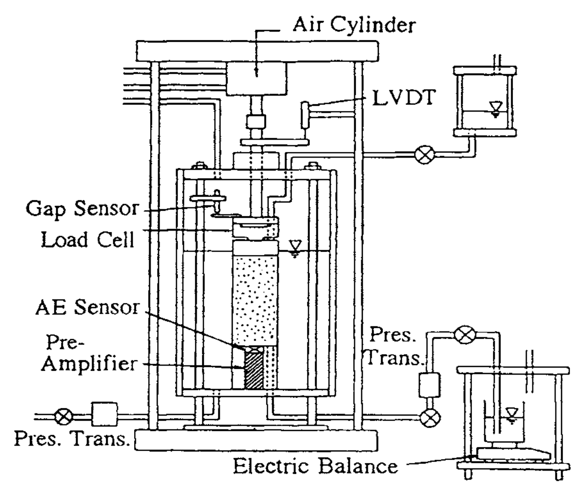


Fig.1 Triaxial Test Apparatus

specimen is 50 mm in diameter and 120 mm in height. The AE signal is monitored by an AE sensor placed in the lower pedestal of the specimen. The sensor has a pre-amplifier and detects minute sounds which are emitted from sand particles sliding against each other. The vertical deformation and axial stress of the specimen are measured directly above the specimen to keep the measurement accuracy as high as possible. The volume change of specimen was measured based on the amount of water expelled from soil by using a highly accurate electric balance.

The soil used in this study is a uniformly graded clean sand, known as Souma Sand. The sand has grain size characteristics of d_{max}=0.85mm, d_{ave}=0.262mm, and U_c=2.036, with the specific gravity of 2.643. The sand specimen was prepared by pouring air dried sample into a mold and the height of pouring sample was adjusted to control the density of specimen. Combination of vacuuming and circulation of carbon dioxide gas before inundating the soil was carried out to increase the degree of saturation for the specimen. The dry density of specimen thus formed was 1.40 to 1.42 t/m^3 which correspond to the relative density of 45 to 50% approximately.

TEST PROGRAMME

The test results as presented in this paper can be divided into the following two series;

a) Undrained and drained shear tests on isotropically consolidated sand.

One of the test series was the undrained shear testing of the sand with an isotropic pre-stressing. In this series, the specimen was first subjected to an isotropic consolidation of 589 kPa and then unloaded to various confining pressures in order to give desired over-consolidation ratios. The specimen was then compressed or unloaded axially under either undrained or drained conditions. During the shear the AE measurements were taken to determine the yield stress of isotropically consolidated specimen.

b) Drained shear test on sand after five full cycles of undrained loading

In the second test series, the specimen was given five full cycles of undrained loading, σ_1-σ_3=+-98.1 kPa in compression and extension, after applying the isotropic consolidation pressure of 392 kPa. The consolidation pressure of this test series was kept lower in this series to have test specimens with low undrained shear strength. Such specimen has resulted in significant pore water pressure build-up under few cycles of undrained loading. After subjecting the specimen to this undrained cyclic loading, the specimen was unloaded isotropically to various over-consolidated states and then the specimen was sheared to failure under drained condition. During the shear the AE measurements were taken to examine the change of yield stress which might have occurred due to the undrained cyclic loading.

Drained shear test on sand with a half or full cycle of undrained loading----- Tanaka and Shirakawa (1993)

In addition to the above test series, presented in this paper are the results of triaxial tests on the specimen experiencing either a half or full cycle of undrained loading after being subjected to the isotropic consolidation. The consolidation pressure was 589 kPa, and the deviator stresses, σ_1-σ_3, applied for the undrained loading are 196 and -98.1 kPa for the compression and extension respectively. The details of this test series have been presented elsewhere by Tanaka and Shirakawa (1993) and therefore only relevant test results will be described here to explain the changes of yield locus due to the undrained cyclic loading. It may be also noted that the Souma sand used in this series had a slightly different gradation and therefore the strength and deformation characteristics are slightly different from the sand in other series.

TEST RESULTS AND DISCUSSIONS

Undrained and drained shear tests on isotropically consolidated sand

A typical result from this test series is presented in Fig.2, which shows the stress-strain relationships obtained from undrained shearing under compression and extension modes on isotropically consolidated specimen. As can be seen from the figures, the deviator stress, q, increases with axial strain, ε_a, rapidly at small strain and then after showing a sharp curvature the q value increases steadily with ε_a. In the extension test, the increase of q with ε_a is abruptly terminated as the pore water pressure increased rapidly resulting in a softening behaviour of soil as shown in the stress-stain curves.

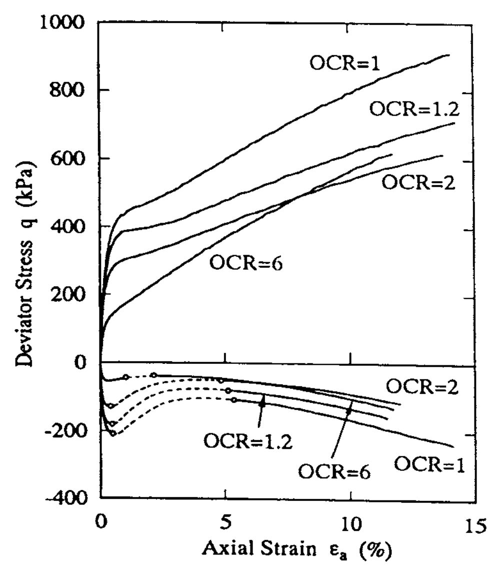
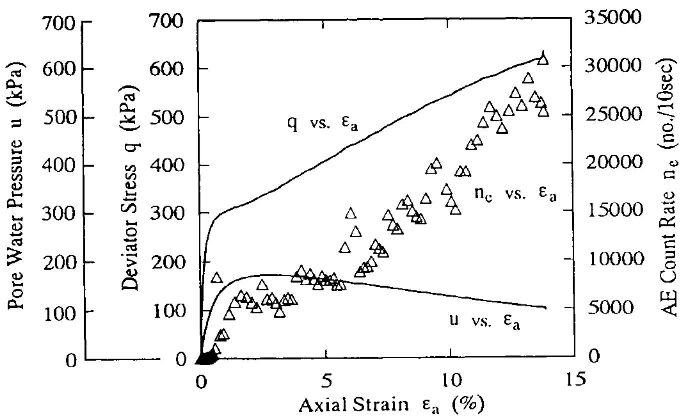
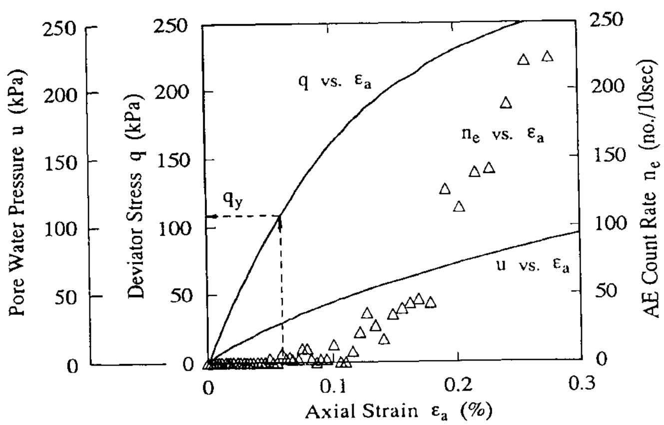


Fig.2 Stress-Strain Relationships of Isotropically Consolidated Sand (Undrained Shear Tests)



(a) q-ε_a, u-ε_a, and AE-ε_a Relationships



(b) Test Results at Small Strains

Fig.3 Typical Test Results of Isotropically Consolidated Sand (Undrained Compression, OCR=2)

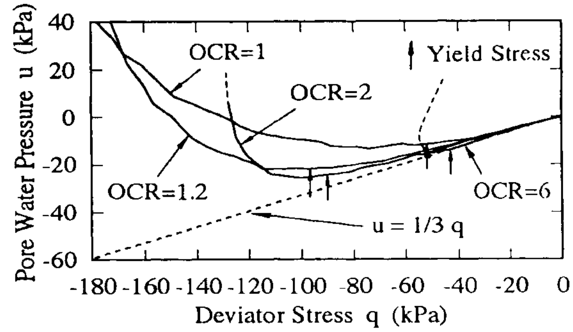


Fig.4 The Relationship between Pore Water Pressure and Deviator Stress

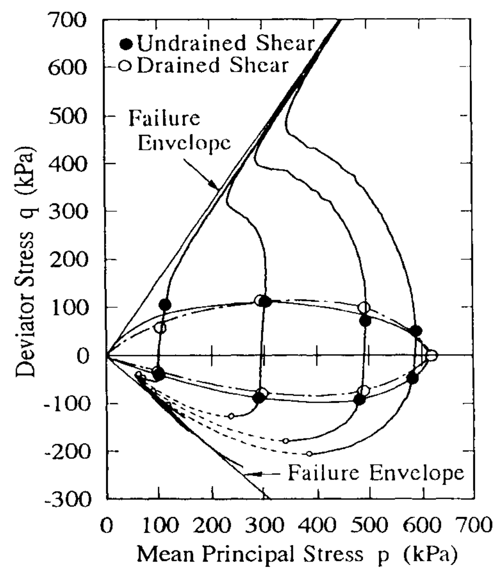


Fig.5 The Yield Locus of Isotropically Consolidated Sand

The AE measurement was taken during the undrained shearing, and a typical test result is shown in Fig.3 (a) and (b). Figure 3(a) shows the increases of deviator stress, pore water pressure and AE with the axial strain at usual magnitude of strain range, while Fig.3(b) shows the same at very small strain range. As shown in Fig.3(b) there are initially increases of strain and pore water pressure without emitting AE as the deviator stress is applied. After the deviator stress reaches some level, the AE starts to be counted indicating some slippages of sand grains. With the initiation of AE, the stress-strain and pore water pressure start to show non-linear responses with the application of load. Since the start of AE represents the starting of irrecoverable deformation, the stress corresponding to the start of AE may be regarded as the yield stress of soil. The pore water pressure responses near the starting of AE are depicted in Fig. 4 which summarizes the undrained test data of extension sides. As can be seen from the figure, the increase of pore water pressure before the yield follows nearly the u=q/3 line indicating the isotropically elastic response, and after the yield as defined by the AE the pore water pressure increases more rapidly deviating faster from the elastic response.

Similar to the results of undrained testing, the test data from the drained testing have indicated the yield stresses of soil at various states of over-consolidation. The yield stresses thus defined are used to examine the yield locus of isotropically consolidated sand. Figure 5 shows the yield locus as defined by the AE measurement and the yield loci from undrained and drained loadings are depicted in the p'-q stress space. The yield loci from the two types of test are almost identical and the shape of yield locus is symmetrical about the p' axis. Similar shape of yield locus has been obtained from different soil type as reported by Tanimoto and Tanaka (1986).

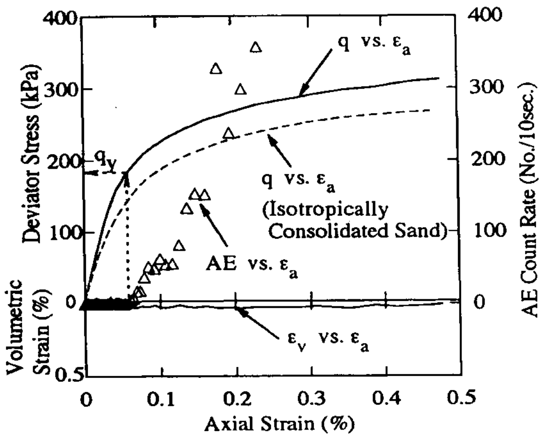


Fig.6 Typical Test Results of Sand with a Half Cycle of Undrained Loading (Drained Compression, OCR=2)

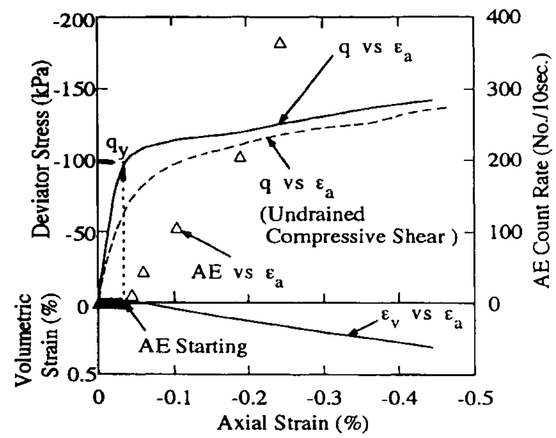


Fig.8 Typical Test Results of Sand with a Full Cycle of Undrained Loading (Drained Extension, OCR=2)

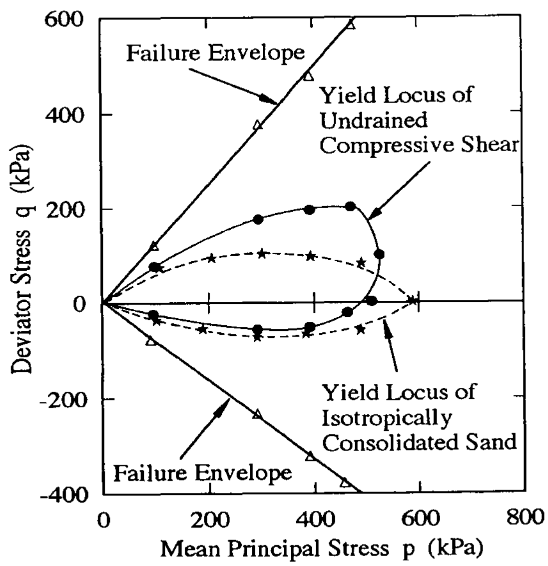


Fig.7 The Yield Locus after a Half Cycle of Undrained Loading

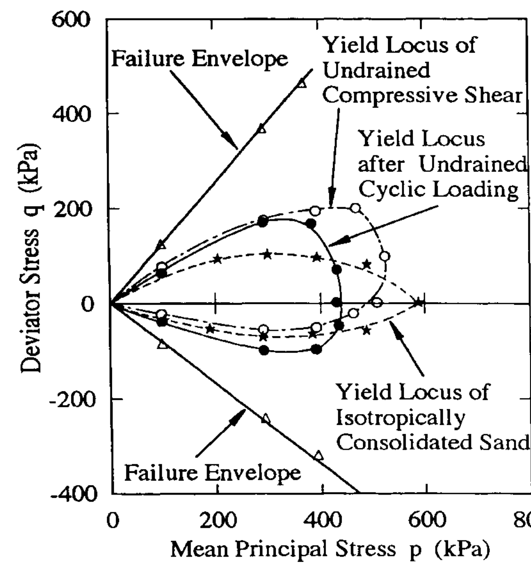


Fig.9 The Yield Locus after a Full Cycle of Undrained Loading

Drained shear test on sand with a half or full cycle of undrained loading

Before presenting the test results of five cycles of undrained loading, presented herein are the yielding behaviours of specimens which are subjected to either a half or full cycle of undrained loading after an isotropic consolidation as reported by Tanaka and Shirakawa (1993). When applying the half of undrained cyclic loading, the specimen was loaded under undrained condition to the compressive side after the isotropic consolidation, while for the full cycle of undrained loading the specimen was loaded first to the compressive side and then to the extension side after the isotropic consolidation. After this undrained loading, the specimen was sheared under drained condition.

Figures 6 and 7 present the typical AE measurement data of a specimen (i.e., OCR=2 and compressive shear) with a half cycle of undrained loading and the resulted yield locus as obtained from the specimens with the same undrained loading. The application of undrained loading has resulted in the changes of soil structure from the isotropically consolidated soil, and the deformation response after the undrained loading is different from the isotropically consolidated case. The difference in soil structure has resulted in the different shapes of yield locus, and Fig. 7 shows clearly that the yield locus has been skewed to the direction of undrained shear.

Figures. 8 and 9 show similar AE measurement data of a specimen (i.e., OCR=2 and shearing in extension) with a full cycle of undrained loading and the resulted yield locus respectively. The difference of deformation response between the specimens with a half and a full cycle of loading is shown in Fig.8, and the higher stiffness is resulted for the

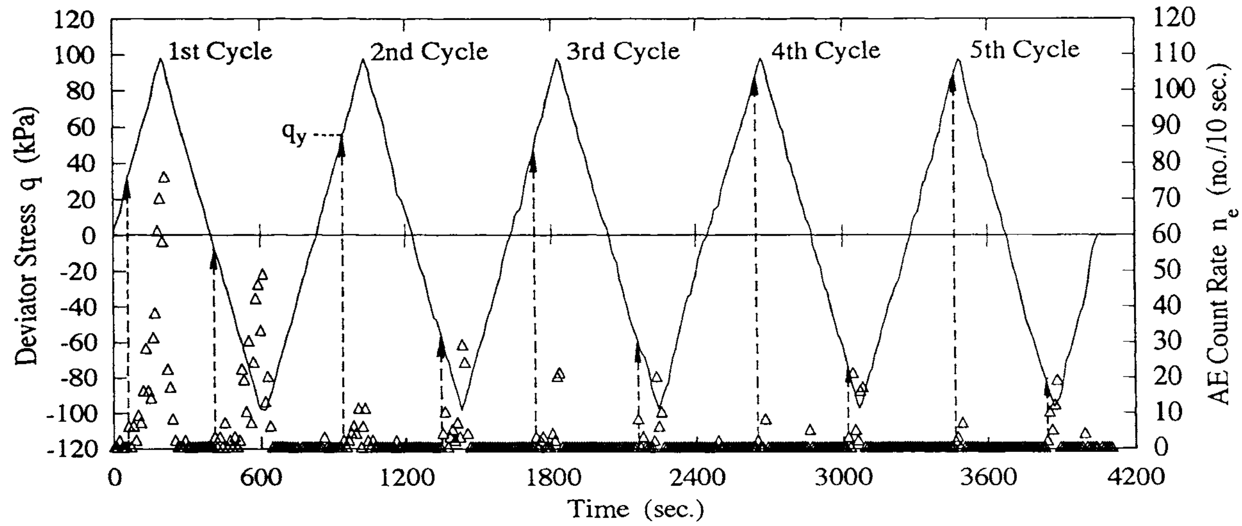


Fig.10 Changes of Deviator Stress and AE with Time during Undrained Cyclic Loadings

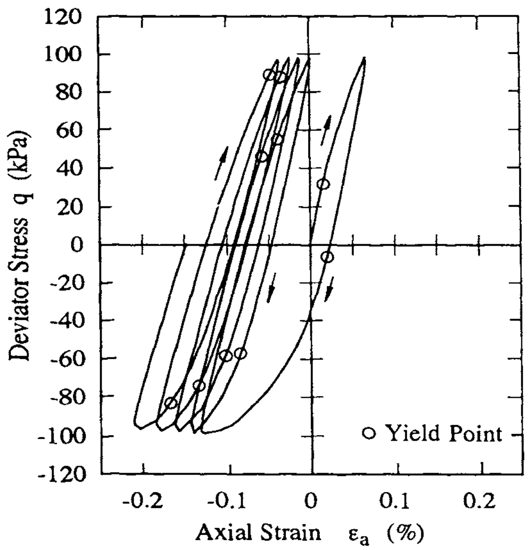


Fig.11 q-ε_a Relationship during Undrained Cyclic Loading

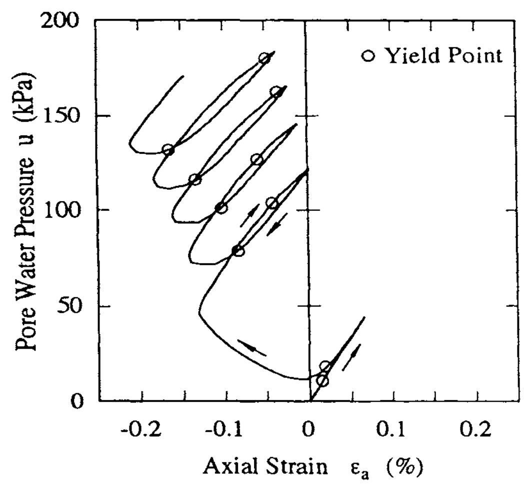


Fig.12 u-ε_a Relationship during Undrained Cyclic Loading

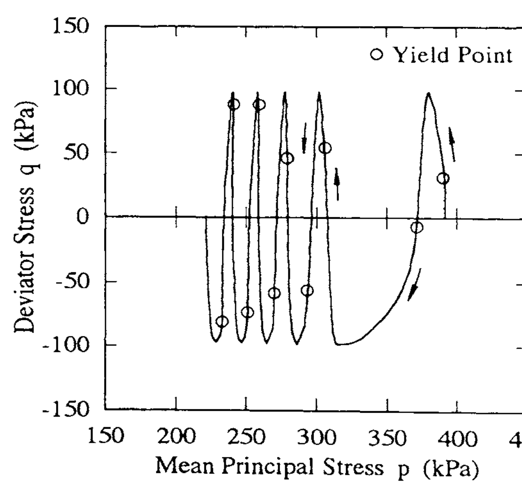


Fig.13 q-p' Relationship during Undrained Cyclic Loading

soil with a full cycle of loading as compared with the soil with a half cycle of undrained loading. The changes in the shapes of yield locus as shown in Fig.9 are more striking. Although the shape of yield locus becomes more symmetric after a full cycle of undrained loading, the size of yield locus along the p' axis is greatly reduced as compared with the one for isotropically consolidated case.

Drained shear test on sand after five full cycles of undrained loading

In this test series, the specimen was given five full cycles of undrained loading after being subjected to isotropic consolidation. The yielding behaviour of sand during this undrained cyclic loading is discussed firstly in the following. Figure 10 presents the sequence of cyclic loadings as applied with time (i.e., loading versus time), and on the same figure the AE measurement results are shown. As can be seen from the figure, the yielding starts shortly after the initial application of compressive load, but the AE stops when the load is started to decrease. However the AE starts again during unloading at the extension side of loading. As the number of cyclic loading increases, the yield stress level at which the AE starts to emit tends to increase as shown in the figure.

In order to illustrate how effective stresses, axial strain and pore water pressure show the changes at the yield stresses, Figs. 11, 12, 13 are produced. These figures present the relationships among the deviator stress, q, versus the axial strain, ε_a, the pore water pressure, u, versus the axial strain, ε_a, and the deviator stress, q, versus the effective mean principal stress, p', respectively. As can be seen from these figures, the relationships among q, ε_a, u, and p' seem to show some signs of non-linearity at the yield stress. The relationship between u and ε_a in particular does show a good agreement between the yield stress and the start of non-linear pore water pressure response.

After subjecting the specimen to five cycles of undrained loading, the specimen was unloaded isotropically to various over-consolidated states and then sheared under drained condition to determine the yield locus. The effective paths applied during the shear are shown schematically in Fig. 14. Figures 15(a) and (b) shows a typical result during shear testing which was taken from a specimen with initial confinig stress of p'=147 kPa. Similar to the shear test result on isotropically consolidated specimen, the AE starts to initiate after some deformation has taken place. It is also to be noted from the figure that the volumetric strain before the yielding of soil shows a sign of expansion while the p' is kept constant for this test. The test on isotropically consolidated sand has shown that the volumetric strain before the yield is almost zero during shear as long as the p' is constant. Thus this behaviour is that of isotropic and elastic material. However, the volumetric strain data of Fig. 15(b) indicates that the sand is behaving anisotropically before the yield. The anisotropic behaviour of sand will be discussed further in the next section. The yield stresses has been determined from all the specimens, and these are plotted on the p'-q stress plane to illustrate the yield locus. Figure 16 presents the yield locus of soil after being subjected to five full cycles of undrained loading, and it can be seen clearly that the size of yield locus decreased very much as compared with the one for isotropically consolidated case.

<u>*Changes of Yield Locus during Undrained Cyclic Loading*</u>

The preceding test results all show that there is a definite effect of undrained cyclic loading on both the shape and size of yield locus. To examine this effect it is necessary to compare the shapes and sizes of yield loci as obtained from the preceding test series. However, as described earlier, the maximum consolidation pressure and also the strength

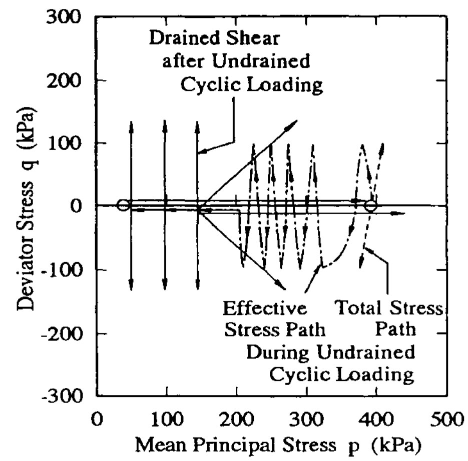
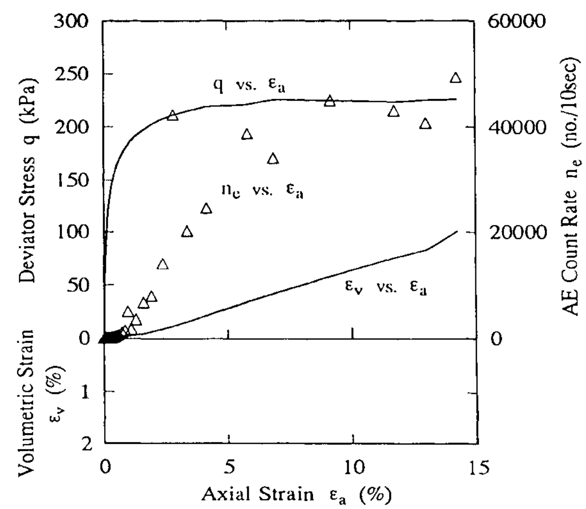
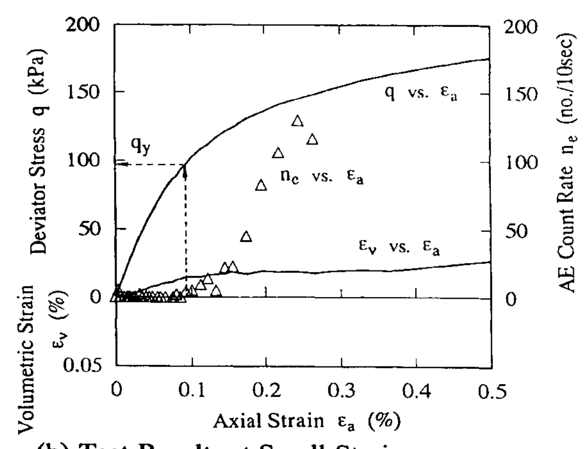


Fig.14 Stress Paths during Undrained Cyclic Loading and Drained Shearing



(a) q-ε_a, ε_v-ε_a, and AE-ε_a Relationships (Drained Compression Test, p'=147 kPa)



(b) Test Results at Small Strains (Drained Compression Test, p'=147 kPa)

Fig.15 Typical Shear Test Results of Sand after 5 Cycles of Undrained Loading

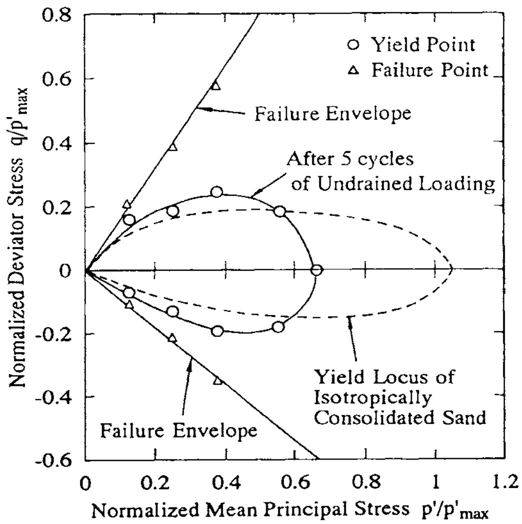


Fig.16 The Yield Locus of Sand after 5 Cycles of Undrained Loading

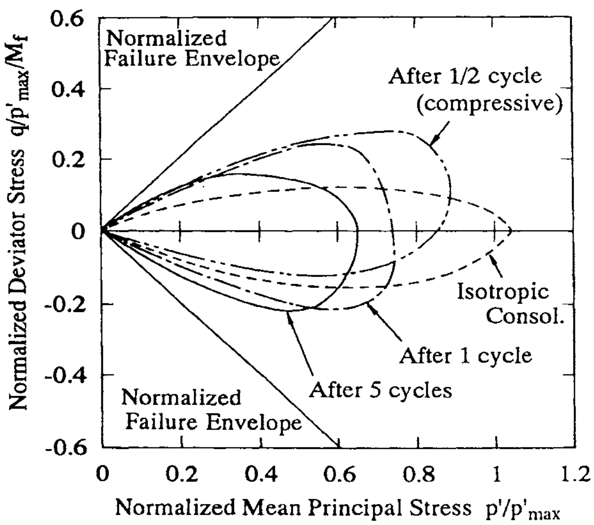
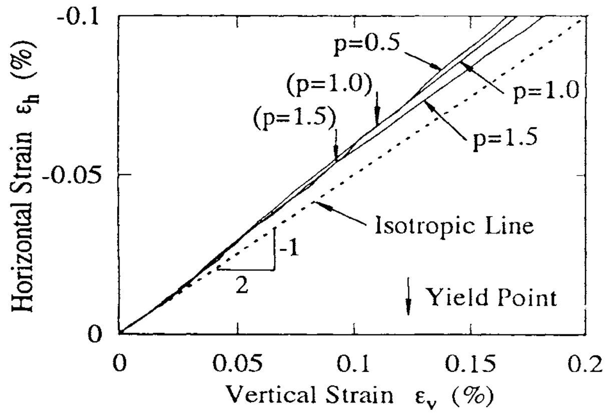
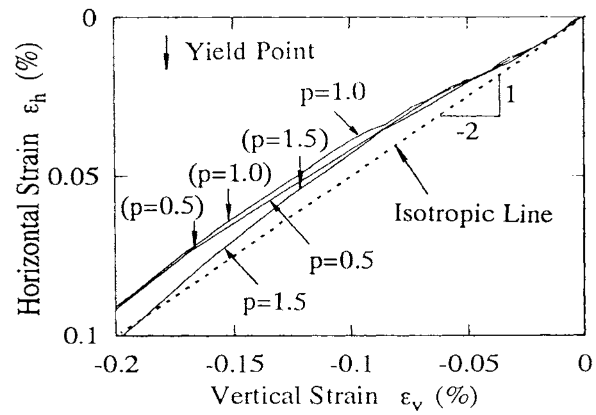


Fig.17 Comparison of Yield Loci of Sands Subjected to Different Undrained Loadings

properties of sands among the three test series vary somewhat. Therefore it was decided to normalize both the consolidation stress and the strength, and by doing so Fig. 17 was produced. As can be seen from the figure, the p' values of each test are divided by their maximum consolidation stress and, for the q values, the stress ratio, q/p'_{max}, is used and this has been divided by their maximum values, $M_f=(q_{max}/p')$, (i.e. the value at failure). Figure 17 clearly shows how the shape and size of yield locus change with the application of undrained cyclic loadings. During



(a) Drained Compression Test, p' constant



(b) Drained Extension Test, p' constant

Fig.18 Horizontal and Vertical Strains of Sand after 5 Cycles of Undrained Loading

the undrained cyclic loading, it seems that the yield locus constantly reduces its size and changes its shape according to the direction of undrained loading. Such changes of yield locus would impose that the part of undrained loading path moves from the elastic zone to the plastic zone during cyclic loading, thus generating always positive pore water pressures for contractive soils. The AE and pore water pressure data as indicated in Figs.10 to 13 supports this hypothesis.

In addition to the changes of yield locus during undrained cyclic loading, the changes of deformation characteristics may be important for the sand to accumulate pore water pressure during the cyclic loading. As noted in the previous section, the drained deformation characteristics as in Fig.15 (b) showed a sign of anisotropic behaviour. These deformation data during the drained shear are used to caluculate the soil strains before the yield in vertical and horizontal directions as shown in Fig. 18 (a) and (b) for compression and extension tests respectively. The figures clearly show that the sand behaviour is the one typical for anisotropic and elastic material and it tends to deform easily in horizontal direction than the vertical. This type of changes in deformation characteristics during the undrained cyclic loading needs to be studied further.

CONCLUSIONS

In this paper, the yield locus of sand being subjected to several cycles of undrained loading was investigated by performing the undrained triaxial cyclic tests with the measurement of the AE. The test results indicate the followings;

1) During the undrained cyclic loading, it seems that the yield locus of sand constantly changes its size and shape. It is important to note that the undrained loading has reduced the size of yield locus and changes its shape according to the direction of undrained loading.
2) The AE measurement during the cyclic loading indicated that the yielding occurs constantly during the loading and there is a good agreement between the yield stress and the start of non-linear pore water pressure response.
3) The deformation characteristics of sand changes during the undrained cyclic loading, and the isotropic elastic properties of isotropically consolidated sand seem to change to one typical for anisotropic and elastic material. This aspect of soil behaviour needs to be studied further.

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