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Mechanism of sand liquefaction as studied by acoustic emission

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ABSTRACT

The mechanism of sand liquefaction was studied by performing a series of undrained triaxial test with measurement of Acoustic Emission (AE). The AE measurement is a technique to monitor minute sounds which are generated by slippages of sand particles during loading. By detecting the initiation of AE as sand being loaded, the yielding stress of sand can be determined since the AE should indicate the irrecoverable movements of sand particles. Isotropically consolidated sand was subjected to a cycle of undrained triaxial loading first, and then the yield locus of sand after such loading was determined by performing various stress probing tests with AE measurement under drained loading condition. The shape of yield locus of the isotropically consolidated sand before undrained loading was found to be elliptic on the p (i.e., mean principal stress) - q (i.e., deviator stress) stress plane with its axis of symmetry coincides with the p axis. However, the shape of yield locus has been drastically altered after sand being subjected to undrained shear. The yield locus is translated to the direction of undrained shear indicating the kinematic hardening property of sand, but more importantly the size of yield locus has been reduced towards the origin of p stress axis.

INTRODUCTION

The prediction of undrained behaviour of sand during cyclic loading is often made by assuming an elasto-plastic type of soil model. The advantage of this type of model is that the changes in soil behaviour from low level of loading to

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high level of loading can be reasonably made by using a concept of yield locus. At low level of undrained cyclic loading sand does not generate large excess pore pressures, while at high level of the cyclic loading sand often accumulates large excess pore pressures leading to liquefaction phenomena. Ishihara and Okada [1] have for example proposed a soil model which has two yield loci being formed by deviatoric and isotropic loadings, and they predicted the accumulation of pore water pressure during undrained cyclic loading. However, a numerical model for correctly predicting the cyclic behaviour of sand is very difficult to develop and more elaborate models, such as using nested yield surfaces or multiple loading surfaces have been proposed, Prevost [2] and Norris [3]. The success of the elasto-plastic soil model for cyclic loading seems to depend on how accurately the model incorporates the changes of yield locus during the cyclic loading. Therefore more in-depth laboratory work seems to be needed to examine and to establish how the shape of yield locus changes with the undrained cyclic loading. The objective of this study is to examine the change of yield locus during undrained loading by using the AE measurement technique which proved to be a powerful tool to determine the yield locus of sandy soils.

TEST APPARATUS AND PROCEDURE

Triaxial testing apparatus with AE measurement and soil description

The triaxial testing apparatus used for the study is shown in Fig.1. The apparatus is mounted with an ultra sensitive acoustic sensor at the base of the pedestal, and minute acoustic energy emitted from the specimen can be detected during shear testing. The method of counting AE is based on so-called Ring Down method, and the number of AE pulses exceeding a certain threshold value was counted. The AE counts over a specific time period is termed as AE count rate, and in this study the AE counts over 10 seconds is typically used. The threshold level was set slightly above the back ground noises. The axial load to the specimen was given through an air cylinder to minimize the mechanical noise. Thus all the tests in this study are performed under stress-controlled shearing mode.

The soil used for the test is a clean sand known as Souma Sand. It has a maximum grain size of 2 mm and an average grain size of 0.7 mm with a uniformity coefficient of 2.36. The specific gravity of soil is 2.627. A cylindrical specimen, 50 mm in diameter and 100 mm in height approximately, was prepared by pouring dry sand into a mold on the pedestal, and its density was kept at about 16 kN/m^3. The maximum and minimum densities of sand were 17.4 and 15.0 kN/m^3 respectively. The specimen was then given a circulation of

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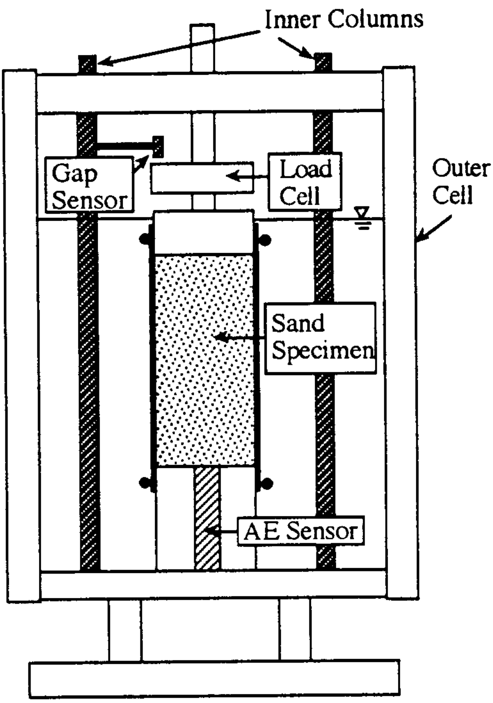

Figure 1: Triaxial Test Apparatus

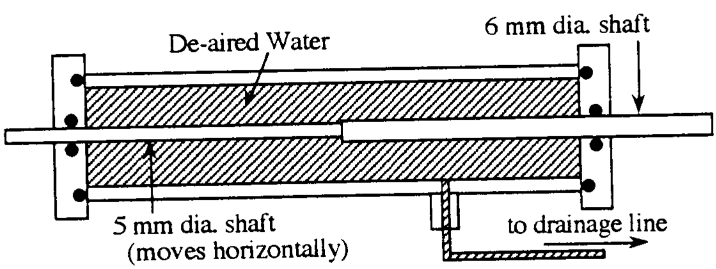

Figure 2: Pore Pressure Correction Device

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carbon dioxide gas for some period, and then a de-aired water was introduced from the bottom of the specimen. By this method, a high degree of saturation was achieved and the B value of specimen was checked before subjecting the specimen to shear. Only the specimens with B value of 0.96 or greater were tested. Also performed in this study is a correction of pore water pressure due to the membrane penetration. The device used for the pore pressure correction is described below.

A pore pressure correction device for membrane penetration

It is widely known that, for shear testings on coarse grained soils, a precaution is necessary to properly evaluate the effect of membrane penetration on the test results. For the drained test, a correction is needed on the measured volume change, and for the undrained test a correction on the measured pore water pressure. Many research works have been reported on the amount of membrane penetration during drained testing, but much less amount of work are available with respect to the effect of membrane penetration during undrained testing.

Tokimatsu and Nakamura [4] for example, proposed a technique to achieve a truly undrained state by performing a drained triaxial testing during which the volume of water needed to counter balance the membrane penetration effect was fed back into the specimen by using an automated back-pressurizing system. Thus the value of back pressure to keep constant volume of specimen was considered as a true pore water pressure for the undrained state. This technique however requires an extremely high precision device for volume change measurement, and some amount of dispelled water, even though it is small, is repeatedly fed back into the specimen. The disadvantage of this system is that the obtained stress path could often become zigzag and the minute volume changes repetitively occurring during the test may have some effects on the subsequent soil behaviour.

In this study, a different approach to the above drained test method was used. The system developed herein uses a water-filled piston which is connected to the drainage line from the specimen. A schematic view of the system and piston is shown in Fig. 2, and the piston has a shaft of which cross-sectional area is changed at the middle (i.e., 5 mm diameter changed to 6 mm). Olsen [5] has proposed a similar system for permeability test for clayey soils in order to achieve a precise control of permeating water. When this piston is not activated during the test, the test becomes an ordinary undrained test with only drainage line closed. However, if we use the piston to feed or expel a very minute amount of water into or out of the specimen to correct the membrane penetration effect, of water into or out of the specimen to correct the membrane penetration effect, we can perform a truly undrained testing. The advantage of this piston is the precision of controlling the volume of water. With the present device, 8.64 mm^3 of water are expelled from the piston while moving the shaft for 1 mm. By monitoring the displacement of the shaft using a dial gauge, the minimum controllable amount water is about 0.43 mm^3.

TEST RESULTS AND DISCUSSIONS

In this study, the following three types of testing have been performed.

1) One of the test series, herein called Series A, was to define the yield locus of isotropically consolidated sand under undrained shear.
2) The second test series, herein called Series B, was to define the yield locus of sand which was given an undrained pre-shearing only to compression side after giving the same isotropic consolidation of Series A.
3) The third series, herein called Series C, was to define the yield locus of sand which was given a full cycle of undrained pre-shearing both in compression and extension after giving the same isotropic consolidation of Series A.

The objective of the above testing program was to establish how the yield locus of sand could change during undrained cyclic loadings in triaxial testing. When we are to simulate the undrained cyclic behaviour of sand using elasto-plastic model, it is very important to find out the way the shape of yield locus changes during the course of undrained cyclic loadings.

Undrained testing on isotropically consolidated soils (Series A)

In this test series, triaxial specimens were consolidated isotropically to a maximum consolidation pressure of 600 kPa and then unloaded to various states of over-consolidations. It may be noted that, at the maximum pressure, the specimen was left under the same isotropic loading for 90 minutes to establish a fully stable soil structure. The ratios of over-consolidation given to the specimen ranged from 1 to 6. After unloading the specimen to various over-consolidated states, the specimens were sheared under undrained condition either to compression side or to extension side, and during the undrained shear the correction was applied to the pore water pressure by using previously described device.

An example of AE measurement during the test is shown in Fig. 3 which is a compression test on specimen with OCR=2. As can be seen from the figure, the

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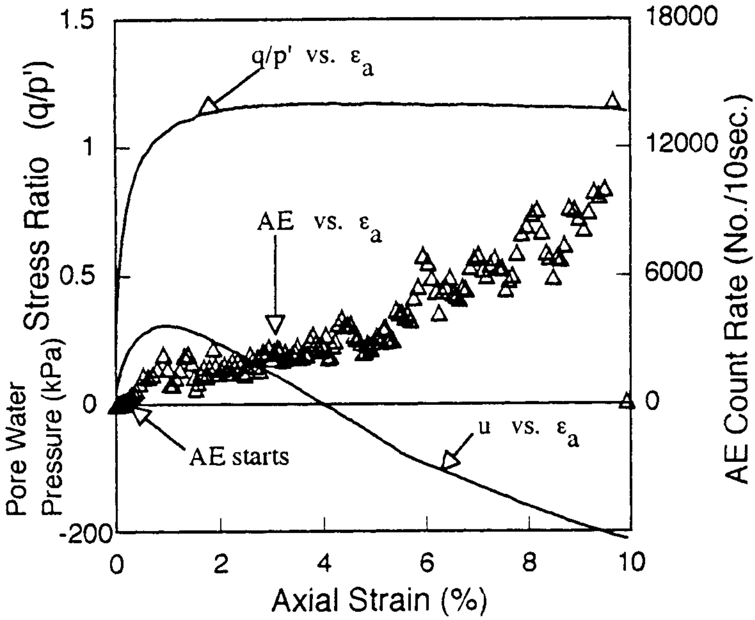

Figure 3: Typical Test Result in Series-A Tests (Compression Test, σ_c=300 kPa)

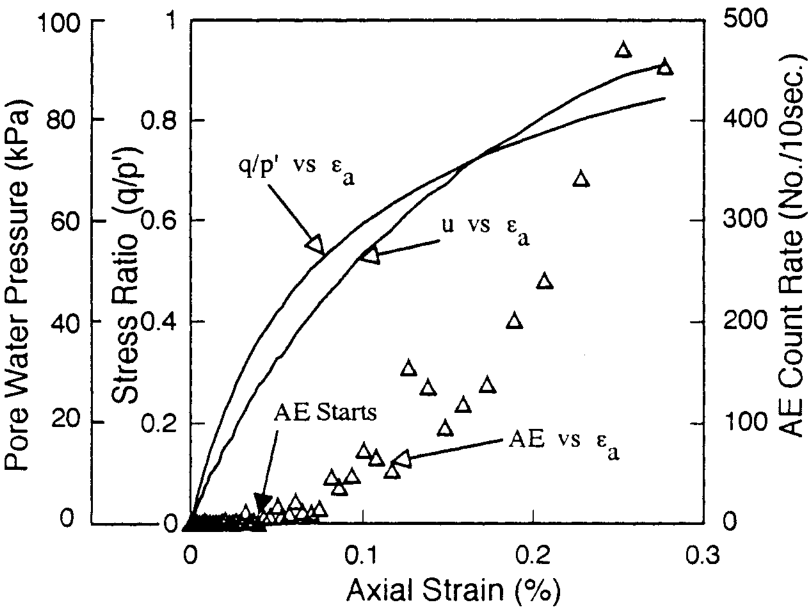

Figure 4: Test Result in Small Strains (Compression Test, σ_c=300 kPa)

AE count rate initially shows zero readings while the deviator stress and pore water pressure are increasing. After the axial strain reaches a certain value, the AE count rate suddenly starts to increase to some level and then the rate of increase decreases somewhat. In order to show the initiation of AE at small deformation range more clearly, Fig. 4 was produced by showing the measurements taken at very small axial strains up to 0.3 %. From this figure, it is clearly seen that there is a certain deformation range during which no acoustic energy is emitted. As has been previously reported by Tanimoto and Tanaka [6], the AE should indicate the slippage of soil particles and therefore irrecoverable deformations. Thus the deviator stress corresponding to the initiation of AE could be regarded as the yielding stress of the soil during undrained shear.

The above procedure was used to obtain yield stresses of all the specimens that were given various over-consolidation ratios. From these data, the yield locus of the soil during undrained loading could be depicted on a stress plane, for example the p (mean principal stress) versus q (deviator stress) stress plane. Figure 5 shows the effective stress paths of all the specimens as depicted on the p-q plane. Also shown as a full circle is the yield stress as determined by the AE measurement. By connecting these data points, the shape of yield locus for isotropically consolidated soil can be clearly seen and it has a shape of ellipse of which longitudinal axis lies on the p axis. A very similar shape of yield locus was obtained by Tanimoto and Tanaka [6] for more compressible sand. It is more striking to note that the effective stress paths below the yield locus are nearly vertical on the p-q stress plane, and it implies that the response of isotropically consolidated sand is nearly showing the behaviour of isotropically elastic material. Previous works on the undrained triaxial testing of sands often show the effective stress path rising somewhat inclined from the vertical. The use of pore pressure correction device for undrained loading may have revealed more isotropic properties of sand when it is consolidated isotropically.

Test results on soils with undrained pre-shearing on compression side (Series B)

In this test series, the specimens were first given the same isotropic consolidation history (maximum consolidation pressure of 600 kPa) of Series A. Then the specimens were unloaded isotropically to 500 kPa, and thereafter were given an undrained pre-shearing to a deviator stress of 200 kPa. At the maximum deviator stress, a holding time of 50 min. was given to the specimens to develop a fully stable soil structure under that stress. After subjecting the soil to the undrained pre-shearing, the specimens were then sheared under drained condition from various states of over-consolidation. The effective stress paths obtained during

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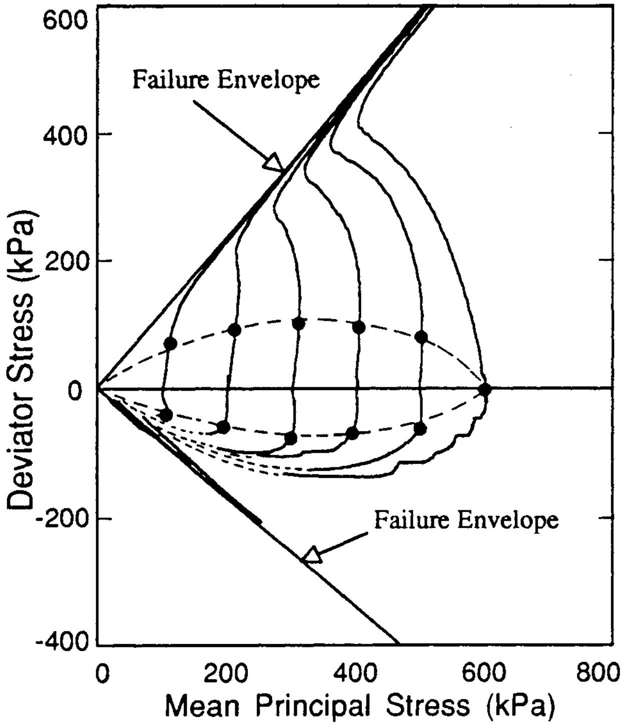

Figure 5: The Yield Locus and Effective Stress Paths (Series-A)

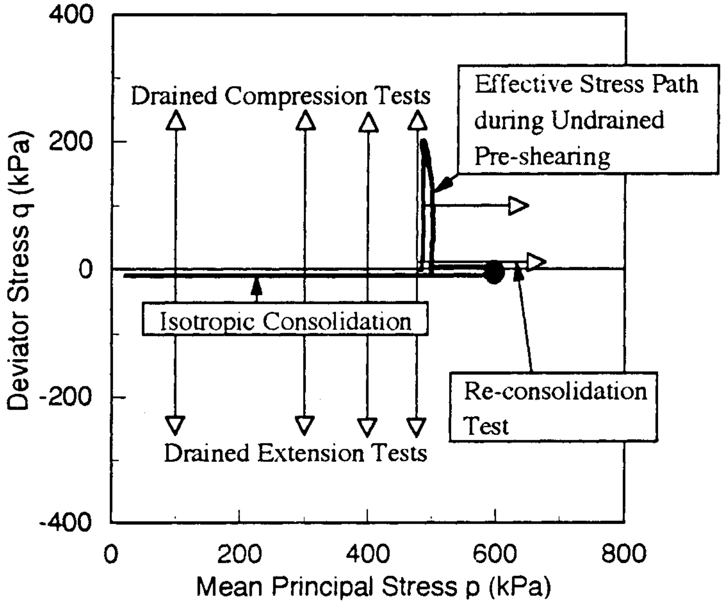

Figure 6: Schematic View of Stress Paths in Series-B Tests

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the undrained pre-shearing and subsequent drained shearing are schematically shown in Fig. 6. The stress paths during the drained shear are mainly of the mean principal stress constant. Exceptions to these are two tests which are performed by increasing only the mean principal stress as described later.

An example of test results is shown in Fig. 7 which presents the data at small strains in the drained compression test on the specimen with initial confining stress of 300 kPa. Also shown in the figure is the stress-strain curve obtained from a drained test on the specimen which has been subjected only to the isotropic consolidation history of Series A. As can be seen from the figure, the initiation of AE occurs after some axial displacement has taken place, and again the yield stress based on AE measurement can be defined. By comparing the stress-strain curves for the specimens with and without the undrained pre-shearing, the yielding stress of soil after the undrained pre-shear does increase due to the increase of the stiffness in the deformation response against compression. The reverse was true for the extension tests. When the specimen with undrained compressive shear was sheared to extension side, the soil did indicated lower yielding stress than that of soil without undrained shear. This is very similar to the conclusion obtained from the soil with drained pre-shearing history, Tanimoto et al. [7].

The yielding stresses as obtained from Series B were depicted on the p-q stress plane, and it is shown in Fig. 8. Also shown in the figure is the yield locus of the soil with isotropic consolidation only (i.e., Series A). As can be seen from the figure, the shape of yield locus is shifted toward the direction of undrained compression shear. As described above, the yielding stress of the soil against compressive stress is increased, and the yielding stress against tensile stress is decreased. It may be noted that the yielding stress points at the right end of yield locus were determined by the two tests in which only the mean principal stress was increased as previously shown in Fig. 6. One of these two tests was an isotropic re-consolidation test, and it did indicated a decrease in the pre-consolidation (i.e., yielding) stress based on the AE measurement. Therefore, the undrained shear has reduced the size of yield locus along the p axis.

<u>Test results on soils with undrained cyclic pre-shearing (Series C)</u>

In this test series, the specimens were first given the same isotropic consolidation history (maximum consolidation pressure of 600 kPa) of Series A. Then the specimens were unloaded isotropically to 500 kPa, and thereafter were given a full cycle of undrained pre-shearing. The magnitudes of shear stress applied in

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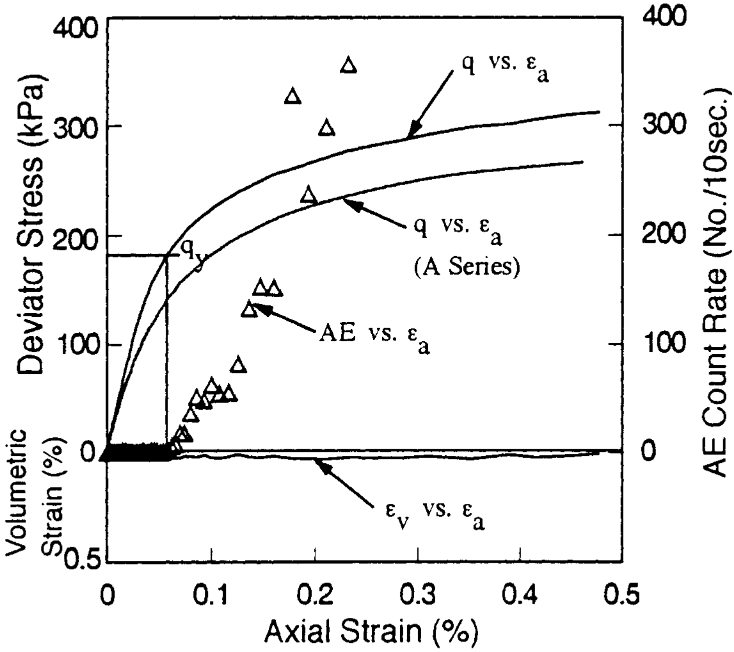

Figure 7: Typical Test Result in Series-B Tests (Compression Test, σ_c=300 kPa)

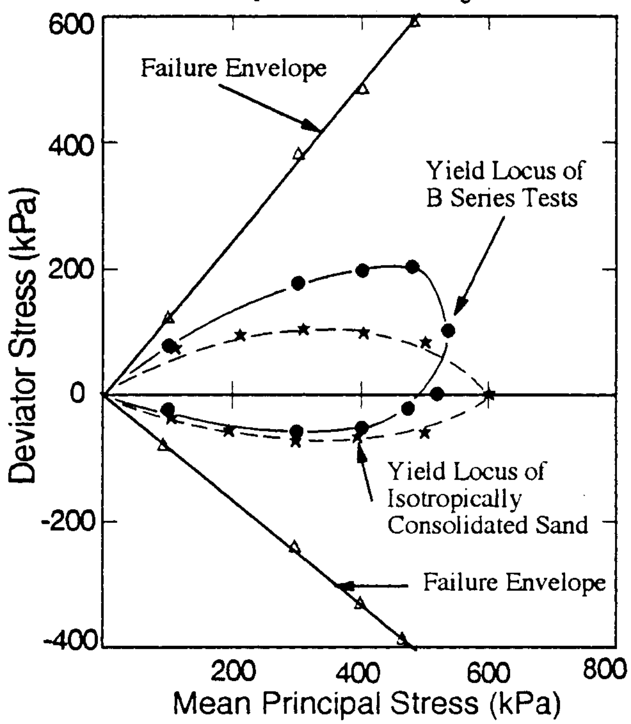

Figure 8: The Yield Locus after Undrained Compressive Shear

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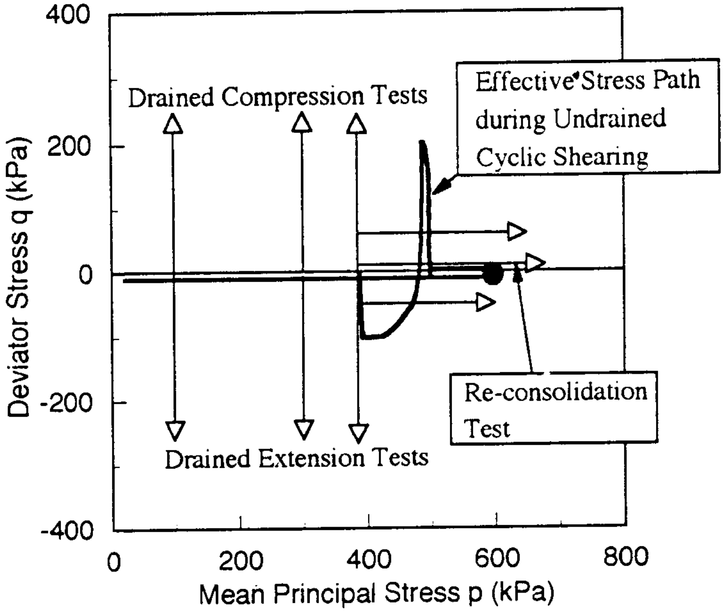

Figure 9: Schematic View of Stress Paths in Series-C Tests

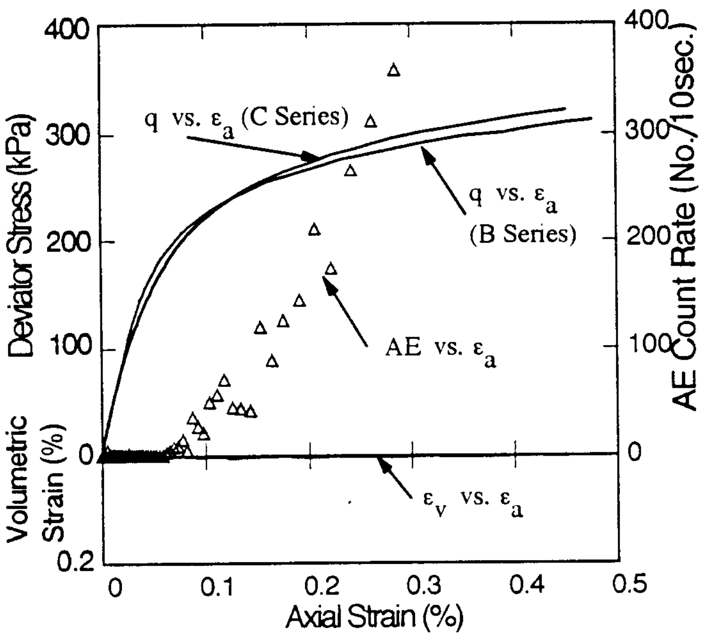

Figure 10: Typical Test Result in Series-C Tests
(Compression Test, σ_c=300 kPa)

compression and extension were however,not the same because of anisotropic undrained strength of the soil. The soil was sheared to a deviator stress of 200 kPa in compressive mode and was sheared to 100 kPa in extension mode. The choice of these stresses was somewhat arbitrary but the strains attained at the maximum stresses were nearly the same. The loading sequences for undrained pre-shearing and subsequent drained shear were nearly identical to those of Series B. Similar to the tests in Series B, at the maximum deviator stress a holding time of 50 minutes was given to the specimens under that stress to develop a fully stable soil structure. The effective stress paths obtained during the undrained pre-shearing and subsequent drained shearing are schematically shown in Fig. 9.

Examples of test results are shown in Figs. 10 and 11 which present the results at small strains of the drained compression and extension tests on the specimen with initial confining stress of 300 kPa respectively. Also shown in these figures are the stress-strain curves obtained from the specimens in Series B. A comparison of the stress-strain responses in compression test (i.e., Fig. 10) does indicate that they are nearly the same, and therefore, at this confining stress range, an addition of undrained tensile loading has not affected the soil's stiffness against compression. On the other hand, the yielding stress of soil in extension side increased due to the full cycle of undrained shear as compared with Series B (i.e., Fig. 11). Figure 12 shows the AE measurement during isotropic re-compression of sample after undrained cyclic shear. The volumetric change was measured but it showed a negligible change. The yield stress is about 440 kPa based on AE while the yield stress was about 520 kPa for Series B and 600 kPa for Series A. The results indicate that the yield stress against shear increases after a full cycle of undrained shear, but on the contrary the yield stress against isotropic compression decreased significantly as compared with those of Series A and B.

The yielding stresses from Series C were depicted on the p-q stress plane, and it is shown in Fig. 13 together with the yield stresses obtained from Series A and B. As can be seen from the figure, the size of yield locus is extended towards the direction of undrained tensile shear. On the other hand the extent of yield locus in the range of higher p stress did show significant changes. Although the yield stress in compression side at confining stress of 300 kPa did not change much as previously noted, the size of yield locus at higher mean principal stress range (i.e, p axis) showed a large decrease. This decrease in the size of yield locus seems to be closely associated with the decrease in the hydrostatic part of

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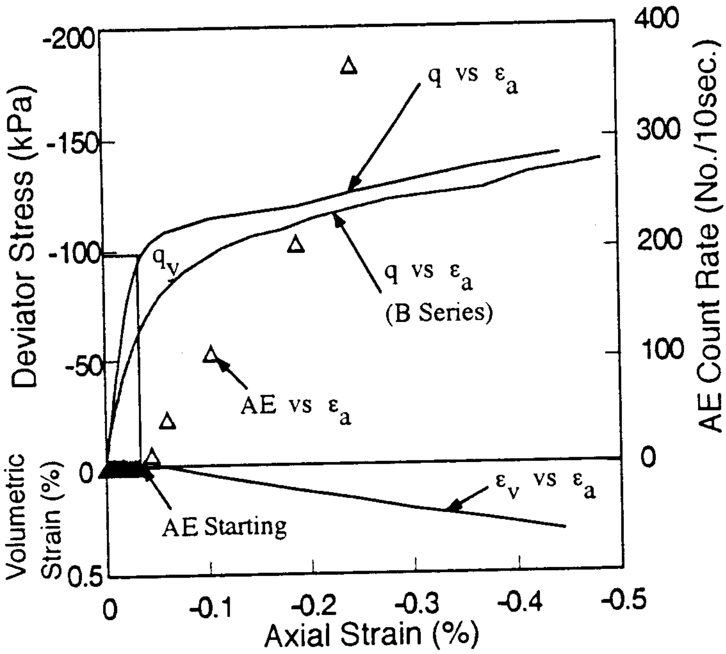

Figure 11: Typical Test Result in Series-C Tests (Extension Test, σ_c=300 kPa)

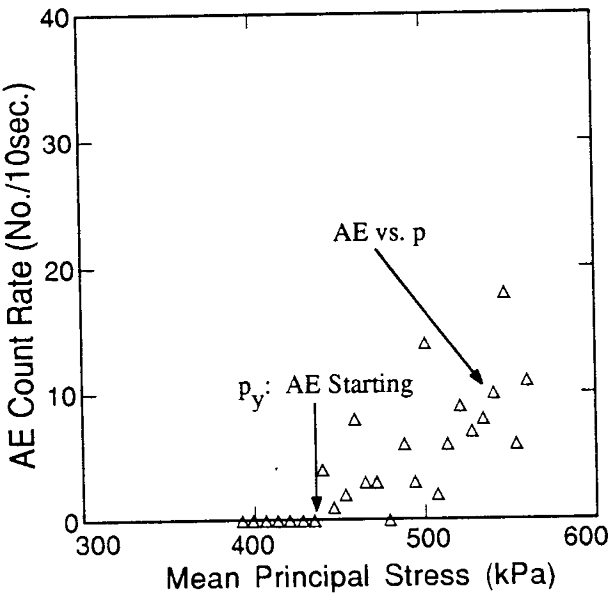

Figure 12: Isotropic Recompression Test in Series-C Test

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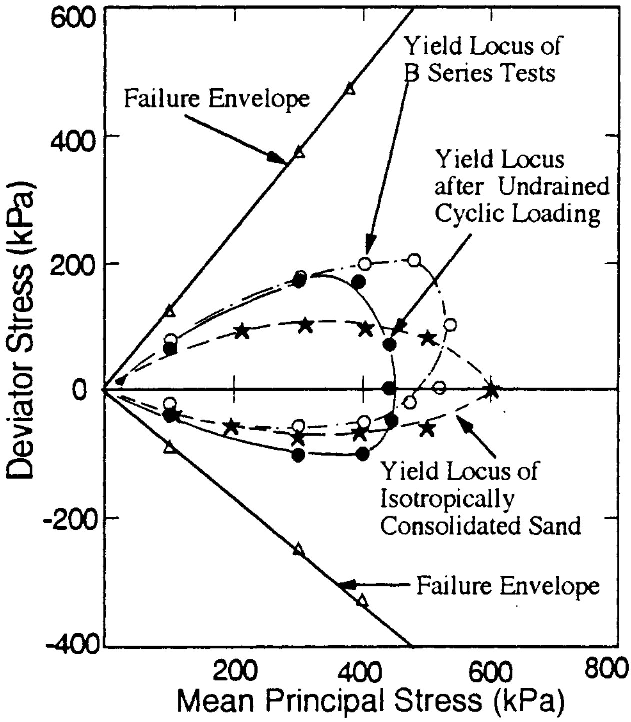

Figure 13: The Yield Locus after a Full Cycle of Undrained Shear

yielding stress as observed from the re-consolidation test.

SUMMARY AND CONCLUSIONS

The test result has indicated a significant reduction in the extent of yield locus which would occur due to undrained cyclic loading. The reduction of the elastic domain within the yield locus would have significant effects on the subsequent undrained cyclic behaviour of saturated sand. It may be envisaged that the continuation of undrained cyclic shear would further decrease the size of yield locus, which eventually leads to the initiation of liquefaction by exhibiting a perfectly plastic response of sand under undrained loading. Thus it is definitely warranted to further examine how the shape of yield locus would change due to several applications of undrained cyclic loading.

Based on the results of this study, the following conclusions may be drawn;

a) The shape of yield locus of the isotropically consolidated sand before undrained loading was found to be elliptic in the p (i.e., mean principal stress) - q (i.e., deviator stress) stress space with its axis of symmetry coincides with the p axis.

b) However, the shape of yield locus has been drastically altered after sand being subjected to undrained shear. The initially elastic and stable stress domain of isotropically consolidated sand has been changed and reduced its size by an application of undrained shear. With the undrained shear to compression side only, the yield locus has been translated to the direction of undrained shear indicating the kinematic hardening property of sand.

c) Much larger reduction in the elastic domain occurred after applying a full cycle of undrained shear, and the size of yield locus has been greatly reduced towards the origin of p stress axis.

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