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A method of determining yield locus of sandy soil

Détermination de la limite d'élasticité d'un sable

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SYNOPSIS Triaxial tests were performed on precompressed specimens of sand with the measurement of acoustic emission. When the specimen was sheared, there was a small elastic deformation at the beginning with negligible acoustic emissions, but the emission increased rapidly as the plastic deformations of soil took place. The yield stress of the specimen was thus obtained simply and furthermore the yield locus of the soil in three-dimensional stress space was determined. The acoustic emission measurements would therefore be a powerful tool for studying the elastic and plastic behaviours of soil.

INTRODUCTION

When a very small load is applied to a material, the deformation due to the load is generally elastic. Upon the releasing of the load, the elastic deformation of the material is fully recovered. However, if the magnitude of the load exceeds a certain limit (i.e., yield level), there will be a plastic deformation of the material. It is generally known, for example Hill (1950), that the most of the energy supplied by the external work that caused the plastic deformations is released externally by the emissions of heat, vibrational or acoustic energies.

To monitor the energy being released from a loaded material, for example monitoring of the emission of acoustic energy, could be a powerful method for studying the elastic and plastic deformation behaviours of materials. This paper is concerned with the use of acoustic emission measurement to examine the elastic-plastic behaviour of soil. A series of triaxial tests were performed on precompressed specimens of sand with the measurement of acoustic emission and the elastic behaviour of soil was examined using a concept of yield locus in three-dimensional stress space, for example Schofield and Wroth (1968).

TEST APPARATUS

A number of triaxial compression and extension tests were carried out using a special test apparatus as shown in Fig.1 and the apparatus is capable of monitoring the acoustic emission (AE) of soil. Much of the details of the apparatus have already been described by Tanimoto et al. (1981) and therefore only the essentials of the apparatus will be described below.

The AE of soil during shear is monitored using a piezoelectric transducer which is mounted in the pedestal of the triaxial cell. The detected AE is at first filtered through, with a high pass filter of 1 kHz, to eliminate the background noises. Then the number of AE is counted using a digital rate meter. The method of counting AE with the rate meter is of ring down method that counts all pulses exceeding a preset threshold level. The number of AE counted over 1 minute period will be called in this paper as AE count rate, n_e.

TEST PROCEDURE

The soil for the test was a well graded sandy soil which was taken from a deposit of decomposed granite. The soil particle is relatively weak as compared with more commonly available beach sands, and the soil with low density showed somewhat a similar behaviour to that of cohesive soils at low range of pressures. The specimens for triaxial test were prepared by compacting the air-dried sample in a mold very loosely to a dry density of 1600 kg/m³ approximately. The specimens were then saturated by applying a vacuum through the top and by introducing de-aired water from the base. The degree

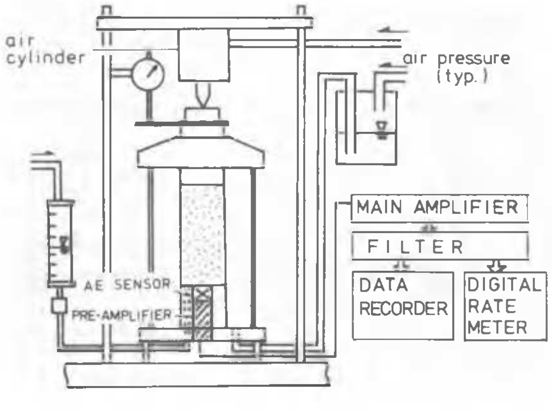

Fig. 1 Triaxial Test Apparatus

of saturation obtained by the above procedure was quite satisfactory and this was confirmed by measuring the pore water pressure response of soil under undrained isotropic loading.

Before subjecting the specimens to shear, an isotropic stress history was given to each specimen. The specimens were consolidated isotropically to a maximum pressure typically of 600 kPa and then the confining pressure was lowered to a suitable level to achieve the desired over-consolidation ratio. After this isotropic pre-compression, the specimens were subjected to shear under compressive or tensile loading with the drainage condition either undrained or drained. The loads were applied by small steps using the air cylinder shown in Fig.1. The cell pressure was kept constant during the loading.

The volume changes of specimen were measured during the isotropic compression for drained triaxial tests and also the pore pressure changes for the undrained tests.

The volume changes which were measured during the isotropic compression stage showed that the compressibility increases very rapidly at pressures greater than 100 kPa approximately, and it was markedly different from that obtained from unloading stage. Therefore it was considered that the specimen was brought into normally consolidated state sufficiently at pressures above 100 kPa.

RESULTS OF DRAINED TRIAXIAL TESTS

A typical result of the drained triaxial compression test is shown in Fig. 2. As can be seen from the figure, the stress-strain curve rises sharply from the start while the AE increases rapidly after some deformations. The deviator stress, q_y, which corresponds to the above sharp increase of AE was obtained from the stress-strain curve.

As described before, the initiation of AE should represent some plastic deformations of the material. It may be hypothesized that for granular materials some elastic deformations with a small load occur due to the straining of soil structures. However, when the load is increased above yield level, there will be relative displacements between individual soil particles that accompany the rotations and the structural re-arrangements of particles. Such displacements of particles would be certainly irreversible, and some energies be released externally to indicate this plastic deformation. The AE measured at small strains would correspond to this release of energy. Therefore, the aforementioned deviator stress, q_y, may be defined as the yield stress.

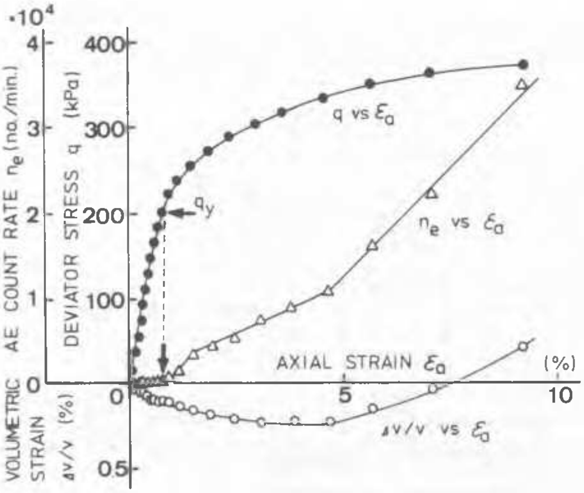

Fig. 2 A typical Result of Drained Triaxial Compression Test (O.C.R.=6)

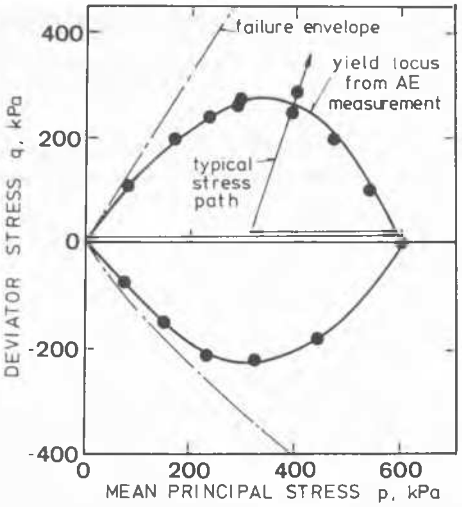

Fig. 3 Yield Locus for Drained Tests

In discussing the yield stress of soils, it would be more appropriate to define the yield locus in the three-dimensional stress space as frequently done to formulate a constitutive model for soil. The various yield stresses are determined for the specimens of different over-consolidation ratios both from the compression and extension tests and the obtained yield locus is depicted in Fig. 3. The yield locus on the compression side has a convex shape above the axis of isotropic stress, p, and the one on the extension side is almost a mirror image of the above.

RESULTS OF UNDRAINED TRIAXIAL TESTS

A typical result obtained from the undrained triaxial compression tests is shown in Fig. 4. Similar to the results of the drained tests, AE starts to increase very rapidly after some displacements have occurred and the corresponding yield stress can be determined on the stress-strain curve. The amount of strain to initiate AE is, however, much smaller than those of the drained tests.

The yield stresses were obtained for the specimens with different over-consolidation ratios and the resulted yield locus is plotted on the p-q space as shown in Fig. 5. Also indicated in the figure are the effective stress paths for the specimens during the undrained loading. As compared with the yield locus for drained test,

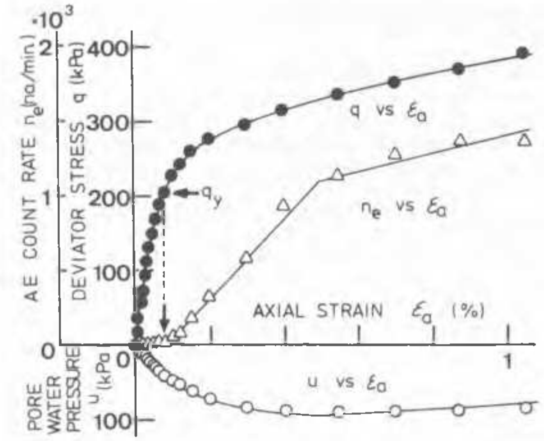

Fig. 4 A Typical Result of Undrained Triaxial Compression Test (O.C.R.=3)

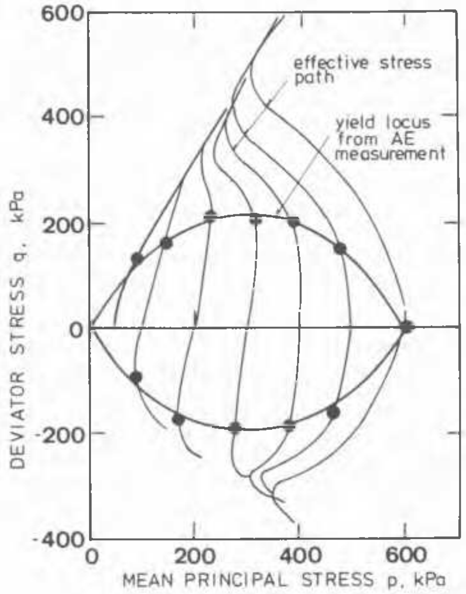

Fig. 5 Yield Locus for Undrained Tests

the one for undrained test shows a very similar shape but a slightly smaller elastic region encapsulating the stress space.

TRIAXIAL TESTS ON PRE-SHEARED SPECIMENS

In the above triaxial tests, the specimens were given an isotropic stress history and the resulted yield locus was approximately symmetric about the axis of hydrostatic stress. It is however a well known fact that the shape of yield locus is affected by various factors such as the shear stress history and time. There seems to be a distinct possibility of applying the AE measurements to study the effects of these factors on the yield locus.

The triaxial tests described above were extended to investigate the effect of shear stress on the yield locus. However, it is not the main purpose of this paper to discuss the details of the yield locus as affected by shear stress history. The results of triaxial tests will be described briefly below only to show one possible application of AE measurements in studying the elastic behaviour of soils.

The specimens for this series of tests were first consolidated isotropically to 400 kPa (Point A as shown in Fig. 6) and sheared after unloaded to over-consolidation ratio of 1.3 (Point B). The shearing was made along the drained stress paths (B-D), but the shear loading was terminated at some predetermined stress level (Point D) after the yielding (Point C) was encountered. Next, the specimens were unloaded (D-B), and then the cell pressure was either increased (for example Point E) or decreased. This was followed by another cycle of loading along the drained stress path (for example E-F).

The yield locus for the specimens with pre-sheared conditions was thus obtained and the resulted locus is shown in Fig. 6. The yield locus for the pre-sheared specimens seems to be somewhat different in shape as compared with that for the specimens with isotropic stress history and the general trend of the results seems to be in agreement with those of other researchers, for example Tatsuoka and Ishihara (1974).

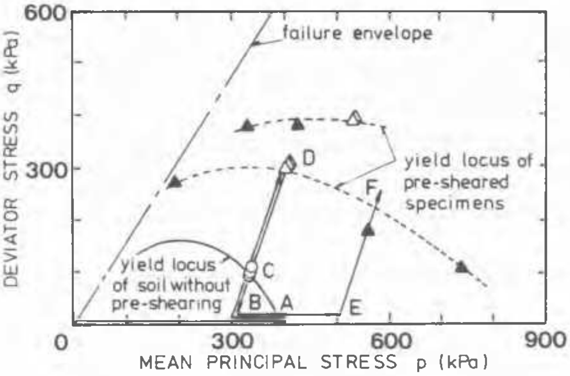

Fig. 6 Yield Locus of Pre-sheared Specimens

DISCUSSION OF AE AND PLASTIC STRAINS

In the foregoings, it was emphasized that the AE measured during the loading of a material reflects the energy released due to plastic deformations of the material. This point is examined further using a result of the drained triaxial tests.

The deformations of soil can be separated into two; the volumetric and shear deformations. The volumetric and shear deformations are usually correlated to the changes of hydrostatic and shear stresses respectively. Fig. 7 illustrates the correlations between these pairs of stress and deformation components during the drained triaxial shear. As can be seen from Fig. 7, the specimen shows initially the small decreases of volume with the increases of isotropic stress, but after some point the decreases of volume become very large. The gentle decreases of volume at the beginning should represent the elastic behaviour as its slope corresponds to the re-compression part of

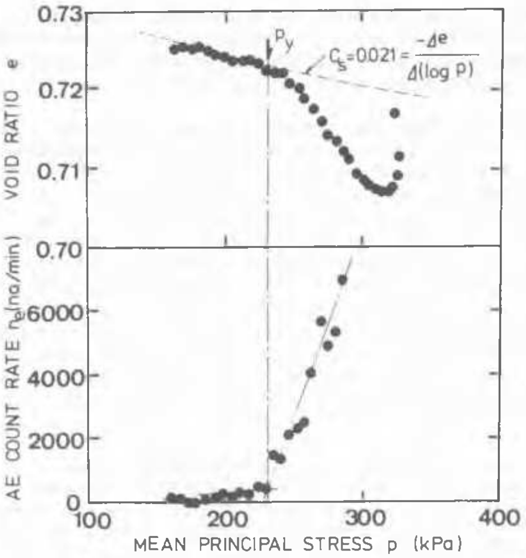

Fig. 7 Relationships among Void Ratio, Mean Principal Stress and AE Count Rate

e-p curve, while the rapid decrease of volume should represent the plastic volume changes.

The lower part of Fig. 7 shows the changes of AE count rate, n_e, with the increase of isotropic stress, p. A sharp increase of n_e can be seen approximately at the same stress level of p that initiated the plastic volume changes.

Similarly the correlationships among shear strain, shear stress and AE were depicted in Fig. 8. As can be seen from the figure, there is a good agreement between a sudden increase of AE and the initiation of plastic shear strain.

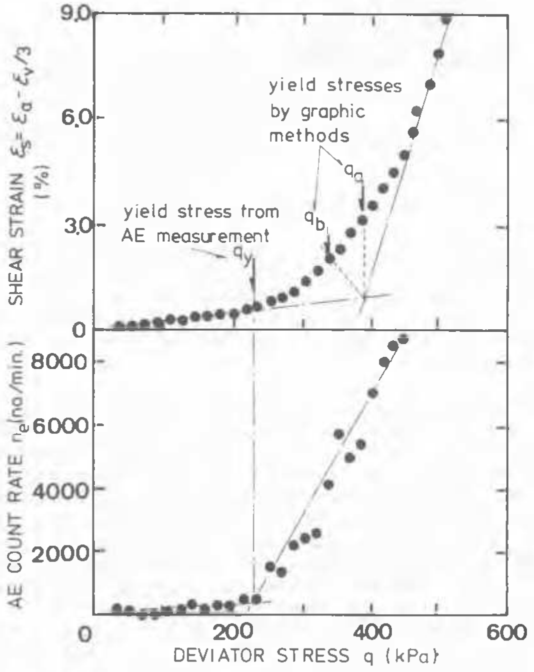

Fig. 8 Relationship among Shear Strain, Shear Stress and AE Count Rate

Also shown in the upper part of Fig. 8 are the yield stresses as determined by the graphical methods which are more commonly used by many others. The methods principally rely on the point of maximum curvature of stress-strain curve. The graphical methods gave much higher yield stresses than that obtained by AE measurements. Also to be noted is that the determination of yield stress much depends on where and how to select the point of maximum curvature, and there do not seem to be much physical meanings in graphics as to decide which is the most suitable method.

CONCLUSIONS

The main conclusions obtained from the experiments may be summarized as follows;

When a precompressed soil is loaded, there is a small elastic deformation that takes place with negligible AE. However, the AE increased very rapidly as the plastic deformations both in terms of volumetric and shear strains of soil took place.

By measuring the AE during triaxial tests, a yield locus of the soil was obtained, and the shape of the locus seems to agree in general with the results obtained by other researchers. However, it should be noted that the commonly used procedures for determining the yield stress of soil make the use of the maximum curvature point on stress-strain curve that does not seem to offer any significant physical meaning. On the other hand, the method with the AE measurement would offer a physical insight to the microscopic changes of soil structure. Furthermore, the yield stress can be determined simply by monitoring AE that gives a sharp rise as the plastic deformation of soil commences.

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