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Cyclic simple shear test and deformation of soils

Essai cyclique de cisaillement simple et déformation des sols

H. H. SCHWAB, Research Engineer, Department of Civil Engineering, Institute of Soil Mechanics and Foundation Engineering, Technical University of Darmstadt, FRG

SYNOPSIS This report gives some remarks to the uniformity or better said the nonuniformity of the states of stress and strain in a soil specimen tested in a simple shear test device. Subsequently, results derived from double simple shear tests are discussed and compared to those from large scale laboratory tests performed on a shaking table at the EERC at Richmond, California (de Alba et al. 1975). Also a link-up was made to hollow cylinder torsional shear tests performed by Ishihara and Yasuda (1975) as well as to similar tests by Ishibashi and Sherif (1974). Finally with respect to anisotropy in the state of stress for two soils, the stress strain characteristics in the case of cyclic loading are reported and discussed, based on results from tests performed in the double simple shear device developed at the Institute for Soil Mech. and Found. Engng. of the Technical University at Darmstadt, FRG.

INTRODUCTION

In the case of cyclic excitation such as during an earthquake for instance, a soil element in the subsoil is mainly loaded horizontally by cyclic acting shear forces. The resulting shear stresses are superimposed on the state of vertically and horizontally acting normal stresses resulting from the weight of the soil mass above the element and as well as from the weight and geometry of structures. The ratio between horizontal and vertical stresses depends on the strength of the soil material and also on possible unloading and reloading caused by geological variations in the past.

case of pore water dissipation. The soil elements B1 to B3 are somewhat more free to lateral deformation so one can expect vertical deformations although there is no drainage of pore water. These vertical deformations take place without the prerequisite of changing stress in the same direction. As it will be shown subsequently in the case of laboratory testing for determining stress strain behaviour of soils, it is necessary to account for the conditions of lateral deformability as described above.

It is generally accepted that the objective of laboratory soil testing is to study the behaviour of a given soil under conditions similar to those encountered in the field using soil specimens as undisturbed as possible. The parameters derived from those tests shall describe this behaviour in a set of constitutive relations. Many testing devices differing in specimen geometry and methods of loading have been developed for this purpose and unfortunately they all are in use for solving practical problems. Because results from laboratory tests only reflect the average soil behaviour, effects of end restraints as well as other boundary conditions included, one has to analyse the states of stress and strain within the test sample. In most of the cases this is not done.

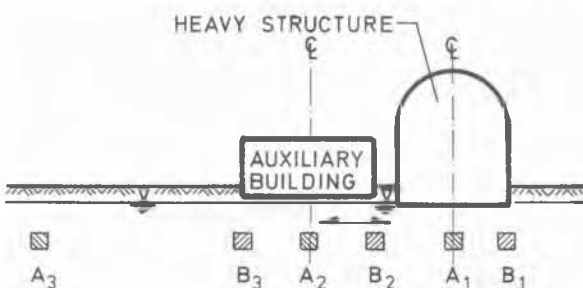


Fig. 1 Soil elements in the subsoil having different lateral confinements.

For example let us consider what is happening to the soil elements in Fig. 1 marked with A and B in the case of a horizontally acting shear stress. The soil elements will deform back and forth as is in simple shear. For the elements A1 to A3 an assumption can be made that theoretically there is no lateral deformation, i.e., neither expansion nor contraction in the horizontal direction will occur. Assuming the soil is fully saturated vertical deformations are possible only in the

ANALYSIS OF THE STATE OF STRESS AND STRAIN WITHIN THE TEST SAMPLE

In the past many testing devices have been developed for investigating soil behaviour under cyclic loading. The most common one is the cyclic triaxial test used for the first time by Seed and Lee (Seed/Lee, 1966). However there are some limitations to this testing device. Two of the most serious ones are the facts that the directions of change in the

applied cyclic stresses always coincide with those of the induced strains and that the mean value of the normal loading stresses increase with increasing shear loading and vice versa (Schwab, 1981). For liquefaction study in the laboratory the simple shear device is generally accepted as the most adequate equipment. Easy handling in trimming the specimens and placing them in the test apparatus makes this device very popular. But there are also many limitations and some of them have to be regarded as severe, which was reason enough for many investigators to make efforts to analyse the distributions of stress and strain in the specimen.

In the last decade a lot of research dealing with hollow cylinder testing was published (e.g. Wright/Gilbert/Saada 1978, Shen/Herrmann/ Sadigh 1978, Shen/Sadigh/Herrman 1978, Ishibashi/Sherif 1974, Ishihara/Yasuda 1975). The main advantage of this testing technique is the provision of a somewhat clearer boundary condition with regard to the complementary shear stress, the lack of which being one of the most serious limitations of simple shear tests. A more complicated

technique in specimen preparation and testing procedure is one of its disadvantages. In this report we refer specifically to a numerical analysis of a specimen with circular cross section tested in a simple shear device. The type of device analysed is the same as used for performing the tests reported later.

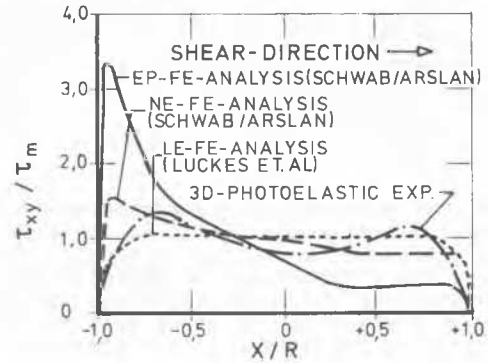


Fig. 3 Shear stress distribution in the center line ($Z=0$) of the base section derived by different methods

An early notation on nonuniformity in the state of stress within a simple shear test specimen was given by Lucks et al. (1972). In their 3D-study based on linear elastic material behaviour they investigated the stress conditions in NGI simple shear test specimens. They concluded that about 70 percent of the sample was found to have a remarkable uniform stress condition. Hara and Kiyota (1977) also presented a 3D-FE analysis based on linear elasticity. They concluded that in the inner part (about 0.70 times radius) the state of stress is uniform. Wright et al. (1978) used Saint Venant's principle and three dimensional photoelastic methods to give theoretically and experimentally some idea of the distribution of stresses in simple shear test samples. Their results seem to imply an unreliability of data interpretation derived from simple shear tests. Experimental research on the measuring of the

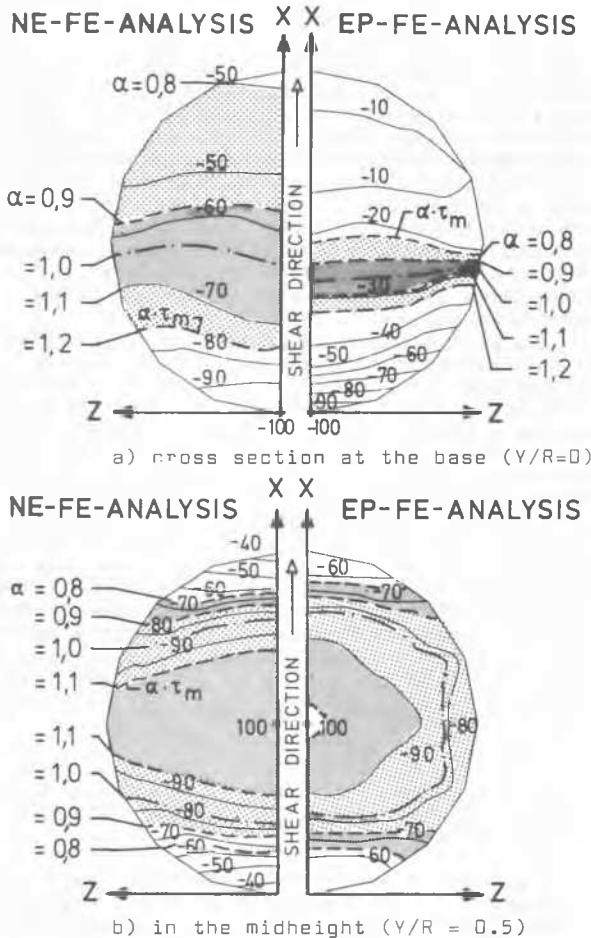


Fig. 2 Shear stress distributions in horizontal cross sections of a circular specimen by nonlinear elastic (NE) and elasto plastic (EP) FE- analysis

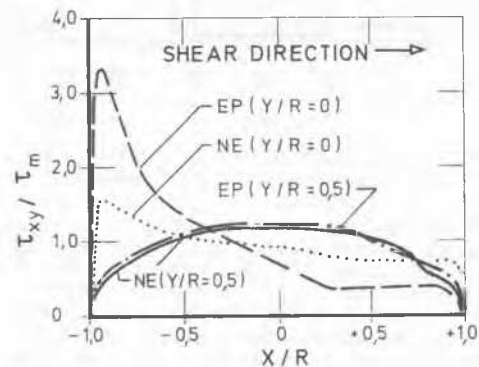


Fig. 4 Distributions of shear stress in the center line ($Z=0$) at the base ($Y/R=0$) and at midheight ($Y/R=0.5$) from NE- and EP-3D-FE analysis.

change in specific conductance during shearing of a specimen in a NGI type device done by Yong et al. (1984) showed a high degree of nonuniformity of the state of strain within the sample. Budhu (1983) finally concluded on the base of experimental studies that one has to expect much nonuniformity in a circular simple shear specimen with regard to the stress as well as to strain. Considering the results of all these investigations one can say that the image of simple shear tests with circular samples proves to be a somewhat negative one. This negative image can not be improved by the results of a 3D-FE analysis using both a nonlinear elastic (NE) as well as an elasto plastic (EP) soil model (Schwab/Arslan, 1985). It was the aim of this study to analyse the stress and strain conditions within the soil specimen in the double simple shear device (DSS) described elsewhere (Schwab, 1974). One of the main differences of this apparatus to the NGI type equipment is the possibility of lateral stress control by a constant cell pressure during consolidation as well as during cyclic loading. Fig. 2 shows the distribution of the shear stress in a horizontal cross section when a shear strain of about 1.7 % was applied. In this figure the iso-lines as percentages from the maximum shear stress are given. From NE- as well as from EP- analysis one can see that there is only a small area in which the shear stress lies within the range of 10 percent from maximum value. It is worse in the EP- analysis and generally in the cross section at the base. Fig. 3 gives the distribution of the shear stress in the center line of the specimen at the base. For comparison, adequate distributions are given in the same graph as reported by Lucks et al. (1972, linear elastic 3D-FE analysis) and by Wright et al. (1978, 3D photoelastic experiments). No further comments seem to be necessary here. Fig. 4 compares the shear stress distributions derived from NE- and EP- analysis for the center line at base and midheight of the sample. Similar results can be given for the state of strain (Schwab/Arslan, 1985). In spite of these, is there a chance for simple shear tests with circular specimens?

DOUBLE SIMPLE SHEAR - LARGE SCALE SHAKING TABLE
 Large-scale shaking table tests as performed by de Alba et al. (1975) are generally accepted as

a very good simulation of free field conditions in the case of cyclic excitation. To make a link-up between those tests and tests with DSS equipment several experiments were performed with a Monterey No. 0 sand as used by de Alba. A description of the equipment, sample preparation and testing procedure is given in an earlier paper (Schwab, 1974). In all the liquefaction tests reported in this section the value of K_0 was chosen to 0.463 which is the theoretical value of an angle of friction of 32.5 degrees. Fig. 5 gives the results of these tests. Relative density was chosen as the curve parameter. Based on the data given in Fig. 5 the diagrams a) and b) in Fig. 6 are plotted. In these diagrams the data from DSS tests are compared with the results from those of shaking table test by de Alba (1975). In spite of the above mentioned limitations in simple shear test devices one can say the results from both systems agree sufficiently.

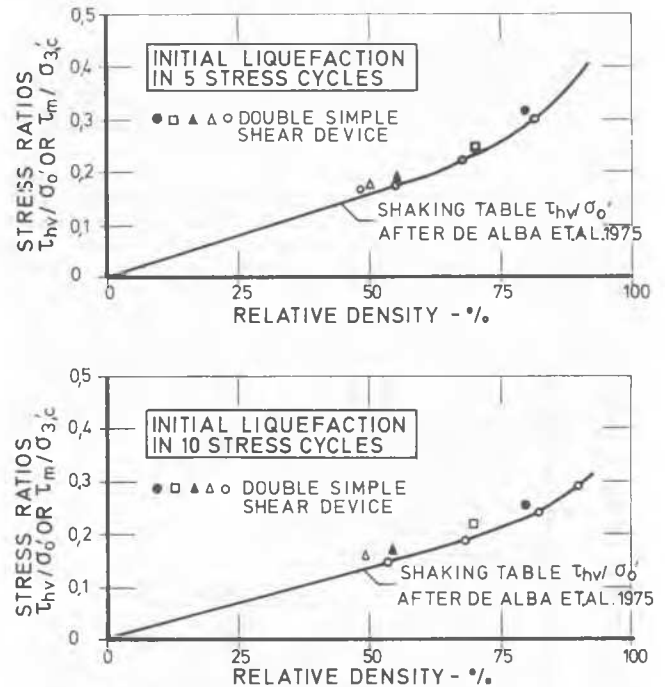


Fig. 6 Liquefaction tests with Monterey No. 0 sand. Comparison shaking table and double simple shear test

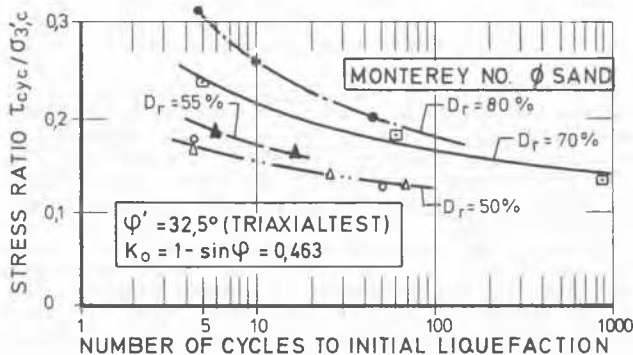


Fig. 5 Liquefaction test results from double simple shear device.

DOUBLE SIMPLE SHEAR - HOLLOW CYLINDER TEST

In a further test series with a DSS device the attempt was made to relate the results to those from investigations in which hollow cylinder testing devices were used. It was one of the aims of the tests to give an answer as to whether or not the influence of K_0 on soil behaviour during cyclic loading can be described in the same way based on test results from DSS tests as well as from hollow cylinder tests. In Fig. 7 the results from three test series performed with a 'silty sand with gravel' in the DSS device are compared to data from other published research. One can see that

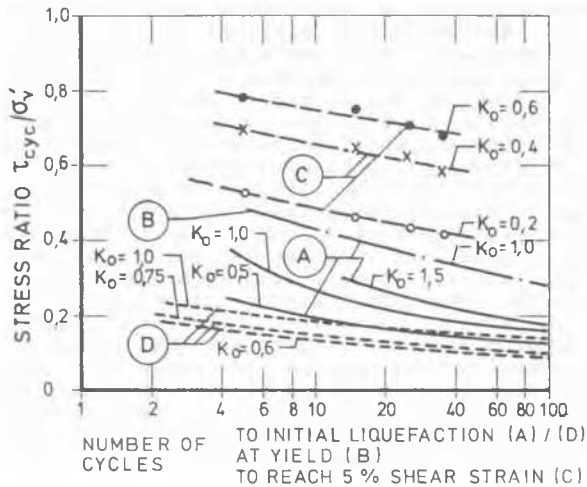


Fig. 7 Cyclic stress ratio/number of cycles

- (A) Fuji River Sand (Ishihara/al. 1979)
- (B) Silty Clay (Ogawa et al. 1977)
- (C) Silty Sand With Gravel (this study)
- (D) Ottawa Sand/ ASTM C-109 (Ishibashi et al. 1974) .

the test results obtained from DSS device are quite similar to those from hollow cylinder devices. If the cyclic shear stress data are related with the mean value of the normal stresses $(1+2K_0) / 3$ one ends with a diagram

apparatus and boundary conditions there is some hope that simple shear testing technique using circular specimen has possibilities for reliable interpretation.

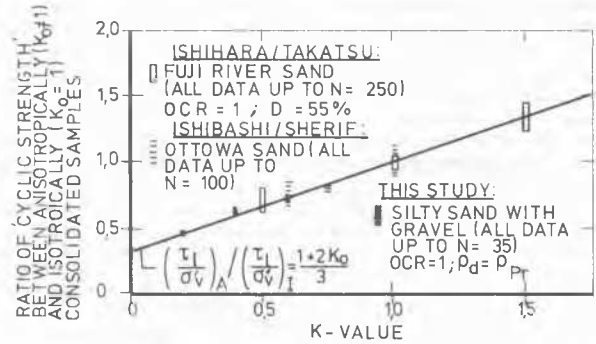


Fig. 9 Influence of cyclic strength due to K_0

SHEAR STRAIN AND SETTLEMENT CAUSED BY CYCLIC SHEAR LOAD

If in a simple shear test the ratio between lateral and vertical total normal stress is kept constant during cyclic loading, the occurrence of shear deformations is accompanied by vertical strains (Schwab, 1981). Similar observations can be made during testing of hollow cylinders as reported by Yasuda (1975).

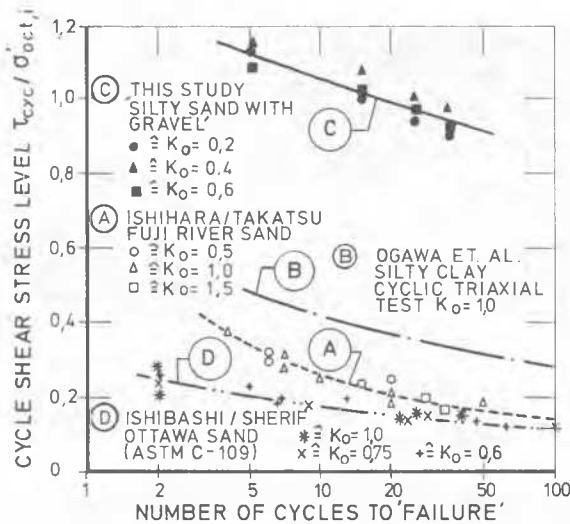


Fig. 8 Cyclic shear stress level versus number of cycles to 'failure' (For identification see Fig. 7)

as in Fig. 8. That indicates, it is possible to describe the influence of K_0 based on results from DSS tests in the same way as can be done for results from hollow cylinder tests. This is shown more clearly in Fig. 9. The method of presentation proposed by Ishihara et al. (1977) was used. The presentation in Fig. 9 shows that in spite of all the limitations in testing

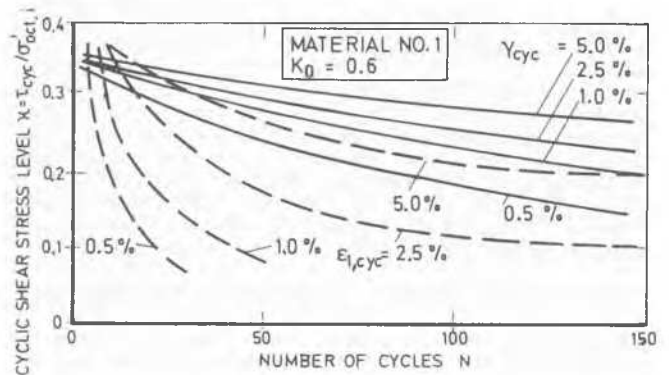


Fig. 10 Shear stress ratio versus number of cycles as a function of shear and vertical strain (material No. 1)

Fig. 10 shows the cyclic shear stress level necessary to cause a certain magnitude of shear and vertical strain in a given number of cycles. The material tested classified as 'weathered rock', consists of sand with about 30 % silt and the same amount of gravel. From data in Fig. 10 the curves in Fig. 11 are plotted. The vertical axis shows the ratio between the cyclic shear stress level necessary to cause a certain amount of shear strain in a given number of cycles and the cyclic shear stress level necessary to cause a vertical strain of the same magnitude in the same number of cycles. This ratio is greater than 1.0; that means the vertical strain is predominant for this material under the chosen testing

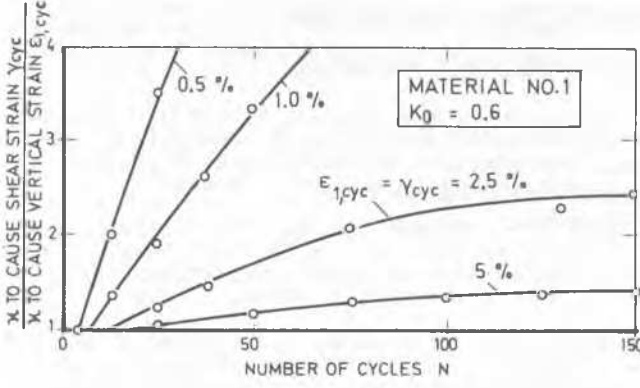


Fig. 11 Comparison of shear stress level to cause vertical and shear strains of the same magnitude (material No. 1)

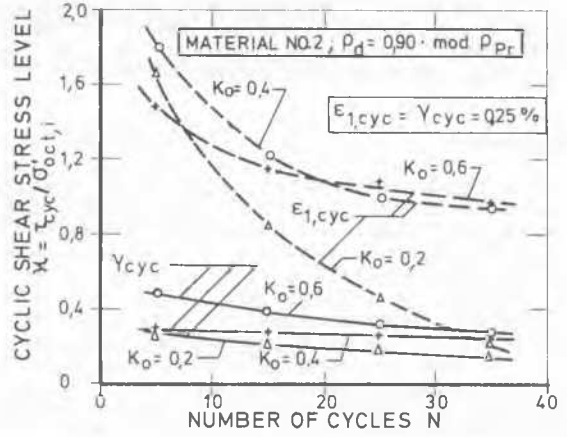


Fig. 14 Influence of K_o -value on cyclic shear stress level at small strains

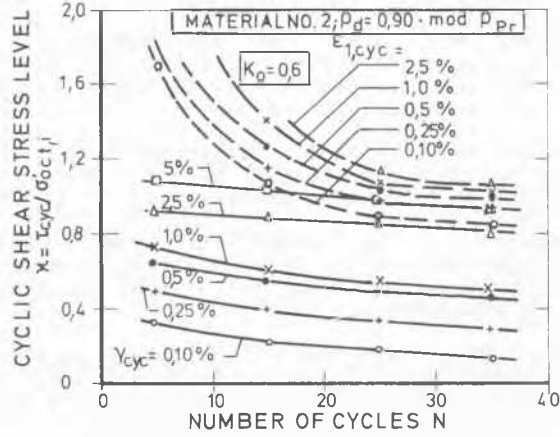


Fig. 12 Shear stress ratio versus number of cycles as a function of shear and vertical strain (material No. 2)

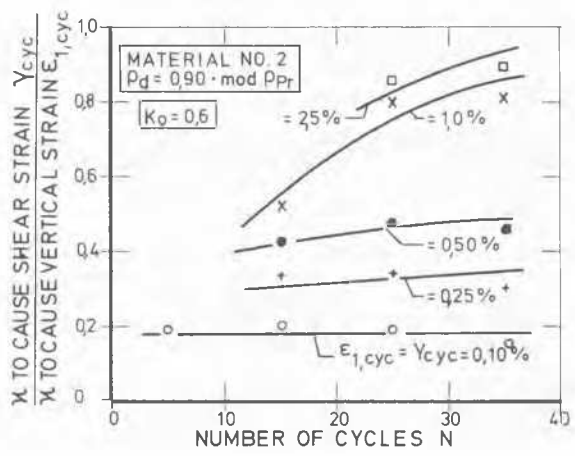


Fig. 13 Comparison of shear stress level to cause vertical and shear strains of the same magnitude (material No. 2)

Fig. 13). This material showed smaller vertical strains than shear strains during cyclic loading. The shear stress level ratio was lesser than 1.0. In all tests the K_o -value was chosen equal to 0.6.

The nonuniformity in the states of stress and strain as mentioned above probably affects the test results at low shear strain as it can be seen in Fig. 14. Using half the scale factor for the vertical axis as in Fig. 8 to plot the cyclic shear stress level, one can see a much larger scattering in the test data as represented in Fig. 14 than in Fig. 8. It is also obvious from Fig. 14 that there is no relationship existing between cyclic shear stress level and K_o -value that can be established with respect to the vertical strain as it can be done in the case of shear strain.

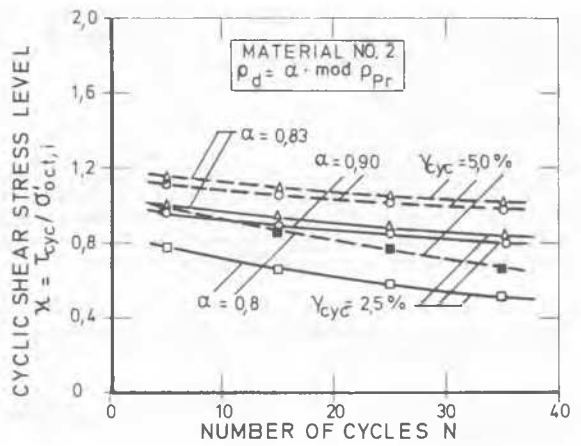


Fig. 15 Influence of dry density on 'shear strength' at large shear strains.

For all tests reported in this section two materials of different densities were utilized but the properties of the specimens were constant. One should note that the dry density of the specimen itself is a parameter affecting the strength and deformation characteristics of the material. Fig. 15 shows as an example how

conditions. In contrast to this, one should consider the behaviour of material No. 2, a 'slightly silty sand with gravel' (Fig. 12 and

the dry density of the specimen influences the cyclic shear stress level to cause a certain shear strain in a given number of cycles. Here a physical relationship is not clear.

CONCLUSIONS

In this paper some data from 3D-FE analysis using a nonlinear elastic as well as an elasto plastic soil model are presented. Compared with research published recently they give reason to believe that there is a high nonuniformity in the states of stress and strain within a cylindrical sample with a circular cross section tested in a simple shear device. In spite of this it was possible to show that the results derived from tests using the DSS device developed at Darmstadt can be correlated sufficiently well to those from large scale shaking table tests. Furthermore it was possible to make a link-up to published test data from hollow cylinder tests. To this one can add, there seems to be some hope for reliable interpretation of results derived from simple shear tests on cylindrical specimens with a circular cross section. For two materials it could be pointed out that not only the shear strains but also the vertical strains have to be taken into account. Shear and vertical strains interact during cyclic loading and rises simultaneously. For settlement and deformation problems it is always important to investigate which one of them is predominant.

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