INFLUENCE OF ANISOTROPY AND STRAIN LEVEL ON THE BEHAVIOR OF A CLAYEY SAND

INFLUENCE DE L'ANISOTROPIE ET DU NIVEAU DE DEFORMATION SUR LE COMPORTEMENT D'UN SABLE ARGILEUX

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SYNOPSIS
This paper presents the results of an experimental research carried out on anisotropically consolidated clayey sand, tested under cyclic undrained loading. The influence of induced anisotropy and strain level on the modulus and pore pressure of soil are discussed herein. The modulus degradation pattern is noticeably affected by both studied effects. Induced pore water pressure, permanent strain and modulus values show a linear relationship with the number of cycles when plotted on a logarithmic scale. The 0.05% strain seems to be an upper bound within which the tested soil shows stiff undrained behavior and a strongly influence of anisotropy on modulus value. When the tested soil undergoes strains over 0.05%, there is a marked loss of stiffness as well as of the influence of inherent anisotropy on the soil moduli. The accurate determination of mechanical properties at strains within the range of 0.001 to 0.1%, is likely to be an important element when analyzing engineering structures subjected to seismic loading and other practical problems. Although, there is a considerable amount of knowledge on soils properties at small strains, more research is required into the influence of anisotropy and time effects on soil behavior during and after strong earthquakes.

INTRODUCTION

The variation on soil modulus during earthquakes may have significant effects on the predicted dynamic response of engineering structures. In order to estimate a building's safety and as a means to estimate subsequent soil deposits response to further earthquakes, back analyses are often performed after strong earthquakes. To perform the analyses, soil properties obtained during site investigation (before building construction), are used. However, after building construction, the original soil properties could have been modified by the effect of several years of consolidation. Moreover, effects due to creep, thixotropy and physicochemical may have a strong influence on soil properties, even in short periods after strong ground motions.

Relatively little attention has been drawn to the study of the combined effects of induced anisotropy, time and strain level on the mechanical properties of soil. The results obtained from a laboratory research on clayey sand samples, consolidated at different anisotropy degrees and tested under cyclic loading in undrained conditions, are presented herein. This laboratory research was carried out in such a way that it allowed to study the mechanical behavior of the compacted soils at small strain levels.

BRIEF REVIEW OF PREVIOUS WORK

It is well known that in some cases drained creep may modify the soil properties in a significant way. The experimental results obtained under isotropic constant mean pressure by Hardin and Black (1968; 1969) and by Anderson and Stokoe (1977) have shown that the modulus increases very fast during primary consolidation and exhibits a linear increase with time during the secondary stage. Anderson and Woods (1975; 1976) pointed out that this behavior responds to the decrease of the void ratio as well as to the effect of thixotropy and physicochemical phenomena. These results, as those of Afifi and Richart (1973) and Stokoe (1980), have clearly shown that the more plastic fines the soil has, the greater the consolidation time effect on the modulus values is. Kokusho et al. (1982) proposed to estimate the shear modulus increment (ΔG) due to consolidation from the plasticity index IP (in percent) and the shear modulus measured at 1000 minutes of consolidation (G_{1000}), as $\Delta G = 0.027\ G_{1000}(IP)^{1/2}$.

Results obtained on anisotropically consolidated clays trimming and tested with different inclinations by Saada et al. (1978) and by Edil and Luh (1980) show clearly that the orientation of the principal stress with respect to the soil fabric on the shear modulus has a significant influence on the soil moduli. Biarez (1962), Wiendieck (1964) and Atkinson (1975), among others, have shown the importance of the initial anisotropy on the mechanical properties of soil. The results of El Hosri (1984) have shown the significant influence that the induced anisotropy may have on the soil moduli.

Macari (1982) observed that the orientation of principal stresses on the axis of orthotropy as well as the overconsolidation ratio, play a mayor role on the shear moduli of a sandy-clayey marine silt of low plasticity. Moreover, his results show that, as well as the moduli degradation patterns have a similar trend for strains less than 0.001% (with relatively high anisotropic to isotropic moduli ratio), the moduli decrease progressively and the anisotropic soil moduli values approach the isotropic one as the strain level increases, indicating a partial suppressing of the inherent anisotropy effect on the modulus value.

It has been conclusively shown, in distinct ways and by different authors, that the soil modulus depend on both the soil fabric (inherent anisotropy) and the orientation of the principal stresses on the axis of orthotropy. Nevertheless, the available results do not yet allow to conclude in a decisive way on the influence of overconsolidation on the modulus at small strain levels. Other aspects, as such as the influence of the number of cycles on the modulus, are of great interest too.

TESTING EQUIPMENT

To measure the confinement and pore pressure at the top and bottom of the specimen, a triaxial cell was equipped with transducers. Displacements were measured with a special device that included proximity inductive displacement transducers, which enables displacement to be measured within a range of $\pm 0.25\ \mu m$ resolution. The transducers were excited using a 10 V a.c. power supply of 5 kHz frequency. In order to allow direct measurement of displacements, the transducers were located into the cell. External linear variable differential transformer (LVDT) transducers were used to check the internal displacement measurements. The resolution of both, the LVDT and proximity transducers, has been determined by calibration using a special micrometer device graduated at $0.01\ \mu m$.

The axial force applied was measured with both external and internal load cells at 1 N resolution. The cyclic load was applied and controlled with a servo-electrohydraulic closed loop machine that can be acted by panel controls or by a microcomputer that performs both control and data acquisition tasks. Data was recorded in real time using several electro-mechanic devices.

MATERIAL TESTED AND CONSOLIDATION

In the case of silty and clayey sands, material properties obtained from undisturbed specimens are generally quite difficult to get. Thus, one faces the task of determining soil properties from reconstituted samples. This work presents some results obtained on soil reconstituted samples using a laboratory compaction technique, to reproduce specimens as those encountered in embankments with the optimum moisture. Consequently, the compacted soil was partially saturated from the very early stages of the triaxial tests.

The tested soil was a brown clayey sand. The clay fraction was of low plasticity. Particle distribution was as follows: 56% of sand in the range of 0.2 to 1 mm, 14% in the range of 0.075 to 0.2 mm and 30% of fines with $w_L=29.5\%$ and IP=8.9%. The compacted specimens tested had the following mean properties: $\gamma_{dmax}=20.15$ kN/m^3, $w_{opt}=9.5\%$, $\gamma_m=22.1$ kN/m^3, $\gamma_s=26.4$ kN/m^3, $S_r=83\%$, e=0.31.

Since the specimens were partially saturated and in order to obtain reliable measurements of pore pressure during the cyclic triaxial tests, they were subjected to flow under a constant pore pressure gradient. The confinement pressure was held at 407 kPa in all tests. The back pressure was held at high values such as 500 kPa. The Skempton B parameter was determined at different time intervals and the saturation stage was stopped when this parameter did not vary in a 24 hour period of time. Typical values of B and saturation degree, after being held under water flow for two weeks, were in the range of 0.93 to 0.96, and of 91 to 98%, respectively. As soon as those parameters reached a stable value, the consolidation stage was started from an isotropic state of stresses. Axial force was then increased to reach a predetermined axial strain. This strain induced an additional anisotropy to the compacted soil specimen.

In order to perform tests at the shortest time and to have reliable measurements of strains at a range of $\pm 0.0005\%$, 70 mm diameter samples were trimmed to reach a slenderness ratio of 1 to 1.2. In order to avoid strain and pore pressure localization phenomena within the sample, smooth-lubricated ends were placed at the top and bottom of the specimen, and the axial strain was induced slowly (about 0.5% per day). When the axial strain reached approximately the prescribed value and some amount of secondary consolidation was taking place, the specimen was removed and weight and volume measurements of the sample was then performed. Afterwards, the specimen was set again in the triaxial cell. Then, the final consolidation stress tensor was applied, and a further consolidation was allowed during one more day. Until then, the cyclic loading test were carried out.

TESTS RESULTS

The results obtained in eight tests are presented hereinafter. Once the consolidation stage was achieved, the specimen was then subjected to cyclic loading in several sets of ten cycles each and was conducted as follows: ten cycles with a constant deviatoric cyclic stress amplitude were applied in undrained conditions and at a frequency of 0.1 Hz. Before the deviatoric stress amplitude was increased by a little amount and another ten cycles were applied to the sample, some time was allowed for pore pressure become stabilized. This operation was continued until a cyclic axial strain amplitude of $\pm 0.5\%$ was reached. For each loading cycle, a hysteresis loop was plotted as a relationship between deviatoric stress and axial strain. The equivalent Young's moduli were obtained from the secant modulus, which represents the average modulus of the loop. The term Young's moduli is not meant to imply that the modulus is strictly elastic, but that it has been considered to be a convenient measure of soil stiffness.

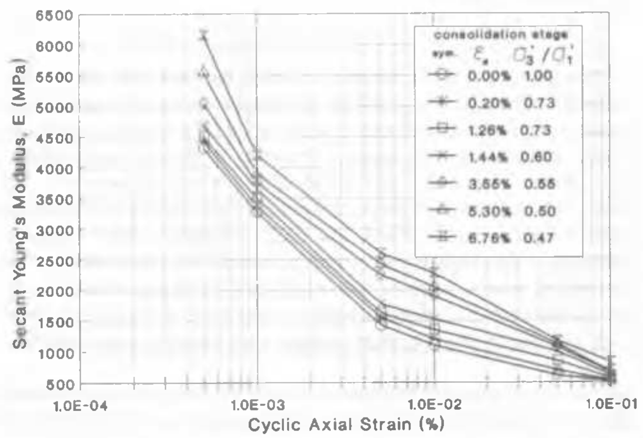

Fig. 1. Variation of Young's Modulus with Cyclic Axial Strain

The variation of the Young's moduli is plotted against the cyclic axial strain amplitude in fig. 1. The results show clearly that the modulus values are influenced by both the cyclic strain amplitude and the anisotropy induced during the consolidation stage. Moreover, the results show that significant amounts of axial strain during the consolidation stage were only possible by decreasing the effective stress ratio ($k=\sigma_r'/\sigma_z'$) from k = 0.73 to k = 0.47, where the values of axial strain were $\epsilon_z=1.26\%$ and $\epsilon_z=6.76\%$, respectively.

The curves illustrated in fig. 1 show that although the axial strain level increases, the modulus degradation patterns follow a similar trend up to cyclic axial strains at a range of 0.0005 to 0.01%. When the axial strain level is larger than 0.01%, modulus degradation becomes more important and the results show that the modulus value of the anisotropically consolidated soil tends towards that obtained on the isotropically consolidated soil. The moduli values are very close when axial strain level is about 0.1%.

The axial strain value of 0.05% may be considered as a threshold under which the soils exhibit very stiff undrained behavior. Thus, it is not possible to observe that behavior in conventional triaxial testing, where the reliable strain measurements are within the range of ±0.05%. However, the later is usually the case in subsoil exploration reports, from which the parameters to perform back analyses of engineering structures are often obtained.

These results show that the more the initial anisotropy is, the higher the soil modulus value. As the strain level increases, the anisotropy can be progressively suppressed and consequently, the high modulus values obtained on anisotropic soil at very small strain levels may be seriously reduced during a strong earthquake loading, which may induce cyclic strain levels at a range of 0.01 to 0.5%.

It is shown in fig. 1 that the variation of the Young's moduli with strain in semilogarithmic scale is roughly linear within the range of 0.005 to 0.1% of strain. The slope of the linear portion of the modulus' degradation curves increase with the importance of the induced anisotropy during consolidation. The ratio $E_{0.1}/E_{0.005}$ varies within 0.35 and 0.42 when the initial effective stress ratio k varies from 1.0 to 0.47, respectively.

The results show that when the strain level is less than 0.1%, the rate at which the permanent strain increases is almost constant. Results as those illustrated in figs. 2 and 3 were typical for all tests.

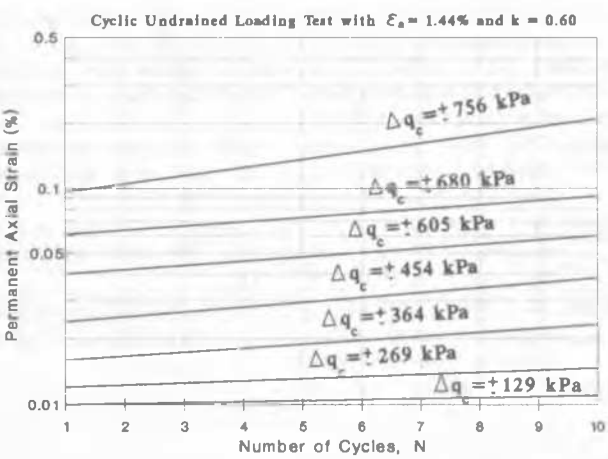

Fig. 2. Variation of Permanent Axial Strain with the Number of Cycles, for each set of cyclic loading

From the results plotted in fig. 2, it can be seen that the permanent strain increases continuously even at relatively small cyclic deviatoric stress amplitude as ±129 kPa. The results show that the domain where the permanent strain rate increases almost constant, is when the cyclic deviatoric stress is within the range of ±364 kPa to ±680 kPa, and corresponds to strain levels between 0.03 and 0.08%.

For the obtained results, a relationship between the permanent strain rate and cyclic deviatoric stress was obtained. This relationship was computed when the strain level is within the range of 0.01 to 0.1% and Δq_c in kPa, as

$$\log_{10}(\epsilon_{N10}^{P}/\epsilon_{N1}^{P}) = \Delta q_c^{1.011}/3000, \qquad 0.01 \leq \epsilon_c \leq 0.1\%$$

A relationship between the cyclic axial strain and cyclic deviatoric stress amplitudes, obtained form all tests performed on anisotropic soil, was computed as follows (Δq_c in kPa),

$$\epsilon_c = (\Delta q_c/3931)^{1.45}, \qquad 0.005 \leq \epsilon_c \leq 0.1\%$$

From the results of all tests it can be shown that soil moduli decreases with the cyclic axial strain amplitude according with the following equation (E in MPa),

$$E = 393\ \epsilon_c^{-0.311}, \qquad 0.005 \leq \epsilon_c \leq 0.1\%$$

Almost for all small values of the permanent strain, the obtained results show that soil moduli decrease continuously during the first ten cycles. No data has been obtained to perform the study of cyclic stabilization of the strains and pore pressure. However. the results of cyclic tests reported by Ray and Woods (1988) showed that silty soils exhibit reduction in modulus with the number of cycles even without increase of pore water pressure was measured.

The variation of the permanent excess in pore pressure induced during cyclic loading is presented in fig. 3. It can be observed that the increase in pore pressure is relatively wide and did not have a defined pattern for all tests. This behavior may respond to the fact that the soil was partially saturated.

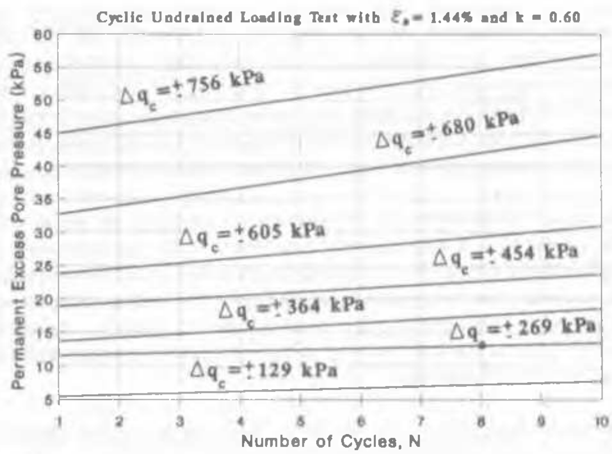

Fig. 3. Variation of Permanent Induced Excess in Pore Pressure with the Number of Cycles, for each set of cyclic loading

Nevertheless, it was observed that pore water pressure increases always during the first 10 cycles almost for relatively small permanent strains. The effective stress paths followed by the tests were nearly straight and not vertical as expected for undrained tests. The effective stress paths are plotted in fig. 4, as well as the one obtained from a test carried out to failure in drained conditions, from an isotropic stress condition. In fact, these results can be explained because the reconstituted compacted samples behave like a lightly overconsolidated, partially saturated soil.

Too few pore water pressure increase measurements have been published for partially overconsolidated soils tested within the range of low strain levels. The results presented herein agree well with those obtained by other Authors, as those reported by Homsi (1986) and by Wu and Richart (1984), who conducted tests on partially saturated soils. The findings suggest that the lower the saturation degree and higher the overconsolidation ratio are, the higher the modulus value is.

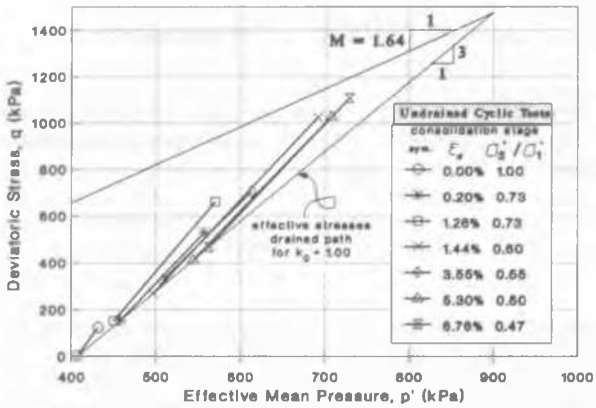

Fig. 4. Effective Stress Paths for the 10th Cycle of Loading

SUMMARY AND CONCLUSIONS

Earthquake induced strains represent an important kind of problems that arises when realistic back analyses and prediction of subsoil displacements must be obtained. When soil behavior exhibits that creep and thixotropy may have an important influence on its mechanical properties, then it is essential to determine how the soil properties may vary between different earthquakes. Another kind of problems may arise from the lack of knowledge on the influence of the anisotropical consolidation that being taken place after building construction; particularly when the mechanical properties used in the analyses have not been obtained for those conditions of stress.

The direct measurement of stress-strain relationships on actual soil samples requires a high degree of accuracy in the measurement of displacements and force at small strains, which is not achieved in the conventional triaxial apparatus usually used for testing samples in routine work. This problem can be overcome if provisions are taken in order to accommodate the force and displacement transducers at the interior of the triaxial cell.

The results described in the preceding paragraphs indicate that the moduli for clayey sands may be influenced to some extent by other factors rather than those usually taken into account (the strain level, grain size distribution of the soil particles, relative density of the soil, and confining pressure), such as the anisotropy induced by strain during consolidation. The results suggest that the overconsolidation ratio as well as the degree of saturation have a significant influence on the increase in pore pressure during cyclic loading.

The results show clearly that the 0.05% cyclic axial strain seems to be an upper bound within which the tested soil shows a stiff undrained behavior and a strong influence of anisotropy on modulus value. When the tested soil undergoes strains over 0.05%, there is a marked loss of both, the stiffness and the influence of inherent anisotropy on the soil moduli. The irrecoverable strain increased progressively during the first ten cycles, even at relatively low strain levels. Moreover, it showed a linear relationship with the cyclic deviatoric stress amplitude during the first ten cycles; i.e., the value of the slope is nearly constant within a range of: $0.005 \leq \epsilon_c \leq 0.1\%$.

The relationships derived herein suggest that for many practical purposes it is possible to obtain useful equations which relate the moduli as a function of the cyclic strain amplitude, as well as the former with the cyclic deviatoric stress amplitude. The results show that the relationships can be expressed as power equations, when obtained from simple correlation techniques. Nevertheless, more research is required on the influence of anisotropy and time effects on soil behavior during and after strong ground motions.

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