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CYCLIC STRESS-STRAIN RELATIONSHIP OF SATURATED SAND CONTRAINTE CYCLIQUE ET DEFORMATION RELATION DU SABLE SATURE

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SYNOPSIS: The cyclic stress-strain relationship of a saturated sand has been investigated by cyclic triaxial tests on consolidated undrained specimens according to five different testing conditions and processes. The results of the tests are represented by the normalized shear stress versus generalized shear strain plots accompanied with the normalized pore water pressure versus generalized shear strain plots and the stress path plots. They are all quite different from each other and can not be embraced by the equivalent linear model. Therefore it is concluded that the reliability and limitations of the equivalent linear model for cyclic stress-strain relationship of soils usually used in the earthquake response analysis of earth structures and foundations are worthwhile to be further investigated.

INTRODUCTION

Nowadays the equivalent linear model for cyclic stress-strain relationship of soils is employed in the earthquake response analysis of earth structures and foundations. However, it is noticed that in this model the quantity of permanent deformation or residual strain has been disregarded which may be significant to the earth body under earthquake action, and the effects of the number of cycles or cycling history and the changing in pore water pressure on the stress-strain relationship of the soil have not been emphasized either. In order to demonstrate these overlooked factors, a series of cyclic triaxial tests have been run on consolidated undrained saturated sand specimens under both stress and strain controlled conditions, which are to be described in the following.

EXPERIMENT

The tests have been run in a manually operated cyclic triaxial testing apparatus. In each test, the cylindrical testing specimen, 3.8 cm in diameter and 10 cm in height, of saturated Fujian Standard Sand of preassigned density was first consolidated under preassigned lateral pressure σ'_{30} and axial pressure σ'_{10} (the consolidation pressure ratio $k'_0 = \sigma'_{10} / \sigma'_{30}$), then the cyclic axial stress of preassigned amplitude $\Delta \sigma_1$ or cyclic strain of preassigned amplitude $\Delta \varepsilon_1$ (with stepped increasing permanent strain in one of the cyclic strain tests) was applied manually to the testing specimen. The values of axial stress σ_1 , axial strain ε_1 and change in pore water pressure Δu were read and recorded for certain specified points in each cycle within each test.

NORMALIZATION OF TEST DATA

According to the definitions of generalized shear stress q and generalized shear strain $\bar{\gamma}$,

$$q = \sigma'_1 - \sigma'_3 = \sigma'_{10} + \Delta \sigma_1 - \sigma'_{30} = (3/\sqrt{2})\tau_{oct} \quad (1)$$

$$\bar{\gamma} = \varepsilon_1 = (1/\sqrt{2})\gamma_{oct} \quad (2)$$

where τ_{oct} and γ_{oct} are octahedral shear stress and octahedral shear strain respectively. The mean effective normal pressure p' can be written as

$$p' = (\sigma'_1 + 2\sigma'_3) / 3 = p'_o + \Delta \sigma_1 / 3 - \Delta u = \sigma'_{oct} \quad (3)$$

where $p'_o = (k'_0 + 2)\sigma'_{30} / 3$ is the mean effective consolidation pressure; σ'_{oct} is the effective octahedral normal pressure. The normalized shear stress is represented by the generalized shear stress ratio

$$\eta' = q / p' = (3/\sqrt{2})\eta'_{oct} \quad (4)$$

where $\eta'_{oct} = \tau_{oct} / \sigma'_{oct}$. The normalized pore water pressure is expressed in the usual way by

$$\Delta u / \sigma'_{30} = (\Delta u / p'_o)(k'_0 + 2) / 3 \quad (5)$$

TEST RESULTS

The Fujian Standard Sand possesses a mean grain size of 0.38 mm with an uniformity coefficient of 1.5. The relative density of each testing specimen has been controlled to be $D_r = 65\%$ and the corresponding effective angle of internal friction has been determined to be $\Phi' = 37.5^\circ$. The test results are presented in the forms of $\eta' \sim \epsilon_1$, $\Delta u / \sigma'_{30} \sim \epsilon_1$ and $q \sim p'$ graphs as shown in Figures 1 to 5 which are the typical results obtained from five tests made according to five different testing conditions.

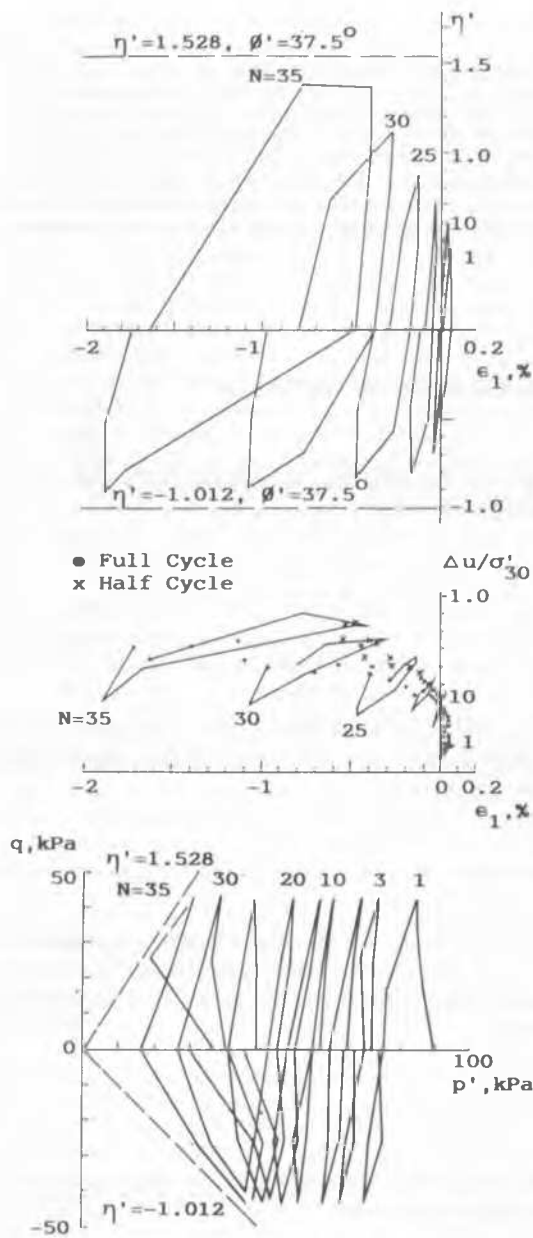


Fig.1. Constant cyclic stress test with $k'_0 = 1$.

In Fig. 1 and Fig.2 are the results of two constant cyclic stress amplitude tests with $k'_0 = 1$ and 2 respectively. They are quite different in appearance. In the $k'_0 = 1$ (Fig.1) test, at the beginning of cycling the strain ϵ_1 is very small and somewhat on the compressional side of the specimen ($\epsilon_1 > 0$), but the pore water pressure ratio $\Delta u / \sigma'_{30}$ rises quite fast; after 10 cycles ($N \geq 10$) $\Delta u / \sigma'_{30}$ becomes over 0.4 and the strain ϵ_1 turns to the extensional side of the specimen ($\epsilon_1 < 0$); after 20 cycles ($N \geq 20$) ϵ_1 becomes beneath -0.1% , $\Delta u / \sigma'_{30}$ becomes over 0.5, and the cyclical variations in ϵ_1 and $\Delta u / \sigma'_{30}$ both increase significantly; at the 35th cycle ($N = 35$) $\epsilon_1 = -(1 \sim 2)\%$, the specimen first

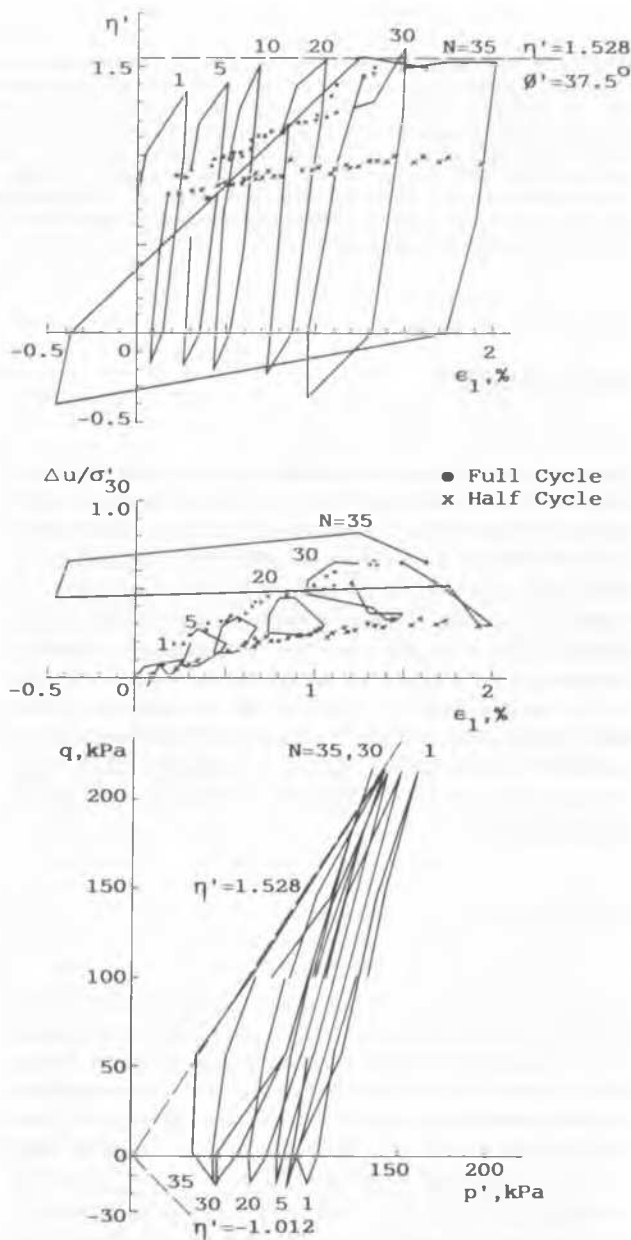


Fig.2. Constant cyclic stress test with $k'_0 = 2$.

approaches the state of limit equilibrium on its extensional side ($\eta' = -1.012$). However, on the other way, in the $k'_o = 2$ (Fig.2) test, after the starting of cycling the strain ε_1 increases only on the compressional side of the specimen ($\varepsilon_1 > 0$) and $\Delta u / \sigma'_{30}$ increases with ε_1 in a relatively uniform rate; within $N = 20 \sim 30$ the specimen first reaches the state of limit equilibrium on its compressional side ($\eta' = 1.528$) while $\varepsilon_1 \approx 1\%$; thereafter, for more number of cycles, the cyclical variations in ε_1 and $\Delta u / \sigma'_{30}$ become larger and even erratic.

In Fig.3 and Fig.4 are the results of two constant cyclic strain amplitude tests with $k'_o = 1$ and 2 respectively. They also show differences. In the case of $k'_o = 1$ (Fig.3), under the action of constant

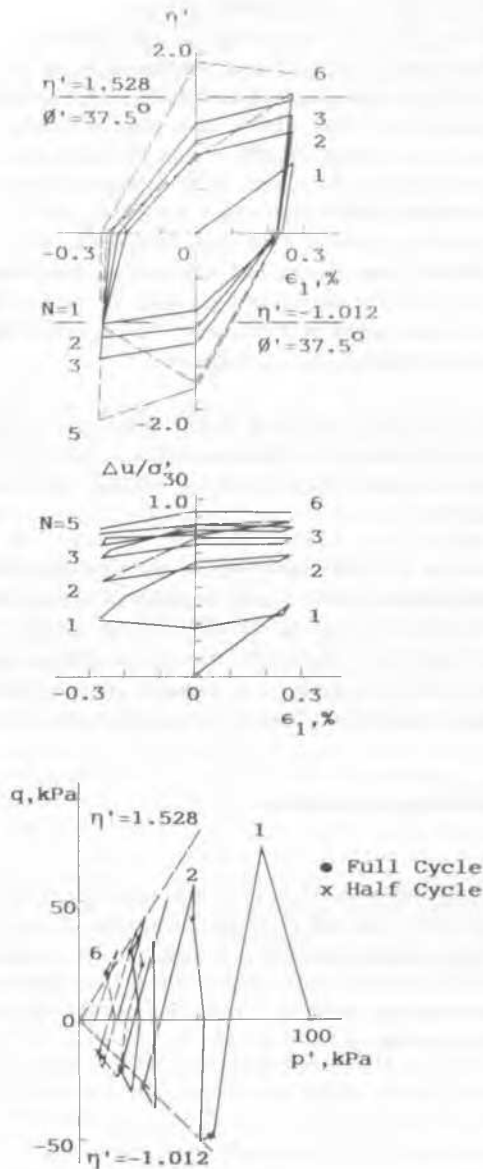


Fig.3. Constant cyclic strain test with $k'_o = 1$.

cyclic strain amplitude of $\pm 0.27\%$ the specimen first reaches the state of limit equilibrium on its extensional side ($\eta' = -1.012$) only at the third quarter point in the first cycle; at the end of the first cycle $\Delta u / \sigma'_{30}$ reaches 0.6; thereafter, in the more number of cycles, $\Delta u / \sigma'_{30}$ increases continuously and the cyclical variation in η' becomes chaotic that may be due to the inaccuracy in the computation of η' when p' approaches zero. In the case of $k'_o = 2$ (Fig.4), as $\Delta u / \sigma'_{30}$ increases gradually with the number of cycles, the cyclic amplitude of η' also increases accordingly; at $N = 60$ the specimen reaches the state of limit equilibrium still on its extensional side ($\eta' = -1.012$); thereafter the $\eta' \sim \varepsilon_1$ loop becomes stationary.

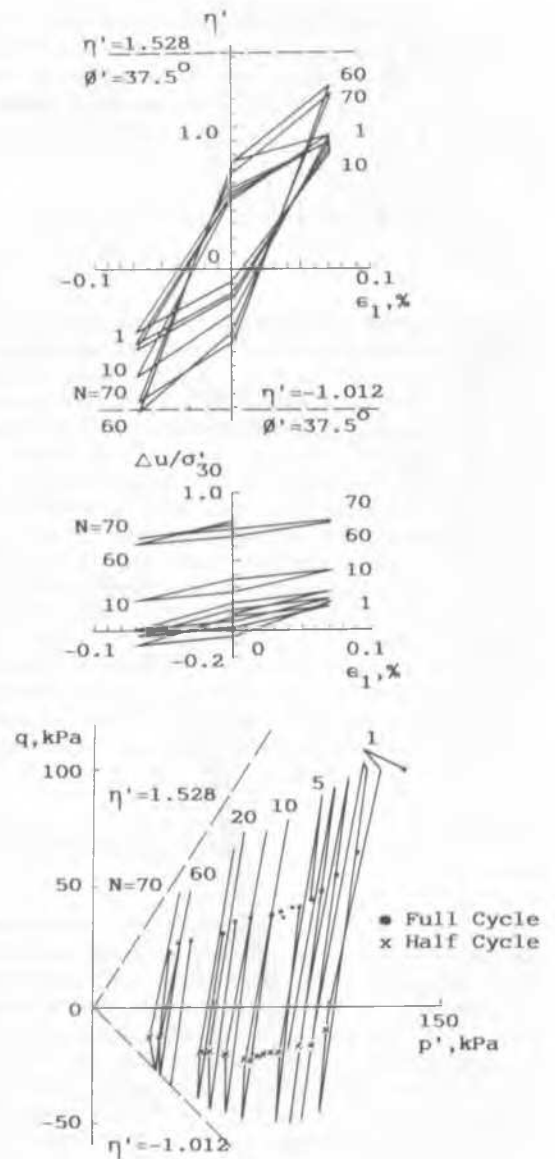


Fig.4. Constant cyclic strain test with $k'_o = 2$.

In Fig.5 is the results of a specially designed test, in which a constant stepped permanent axial strain increment has been added to the specimen at the end of each strain cycle of constant amplitude for the case of $k'_0 = 2$. It can be seen that the configuration shown in Fig. 5 approximates to that as shown in Fig.2, but they are not concordant, because in Fig.2 the increase in permanent strain is not constantly stepped and the cyclic strain amplitude also varies with the increasing number of cycles. However, the specimen still approaches the state of limit equilibrium on its compressional

side ($\eta' = 1.528$) similar to that as shown in Fig.2.

FINAL COMMENTS

Based on the results of cyclic triaxial tests by using different testing conditions and processes, it can be seen that the cyclic stress-strain relationship of a saturated soil is determined by several factors and is rather complex, but there are some traceable rules. In all cases, the pore water pressure rises with the increasing number of cycles, the absolute peak value of η' increases accordingly and approaches the boundary of its state of limit equilibrium, i.e., $\eta = \pm 6\sin\Phi' / (3\mp\sin\Phi')$, where the upper and lower signs are for the compressional and extensional phases of the testing specimen respectively. In the constant cyclic stress amplitude tests (Fig.1 and Fig.2), whatever $k'_0 = 1$ or 2, after $|e_1| > 1\%$, the absolute peak values of η' reach or approach to the boundaries of their state of limit equilibrium and the cyclic loops of $\eta \sim e_1$ expand rapidly or even become erratic, that indicates the oncoming of failures of the specimens. In the constant cyclic strain amplitude tests (Fig.3 and Fig.4), the $\eta \sim e_1$ curves are apparently different from those mentioned above, although the strains e_1 have been limited within certain small values, such as, $|e_1| \leq 0.27\%$ shown in Fig.3 and $|e_1| \leq 0.07\%$ shown in Fig.4, the absolute peak values of η' still can reach the boundaries of their state of limit equilibrium.

In the "Stepped increasing cyclic strain test" (Fig.5), the phenomena comes out to be approximate to that of the constant cyclic strain amplitude test with $k'_0 = 2$ (Fig.2), but they are not concordant.

In view of the wide variations in the configurations of the normalized cyclic stress-strain relationships represented by $\eta' \sim e_1$ curves, it is felt that the reliability and limitations of the equivalent linear model for cyclic stress-strain relationship of soils usually used in the earthquake response analysis of earth structures and foundations are worthwhile to be further investigated.

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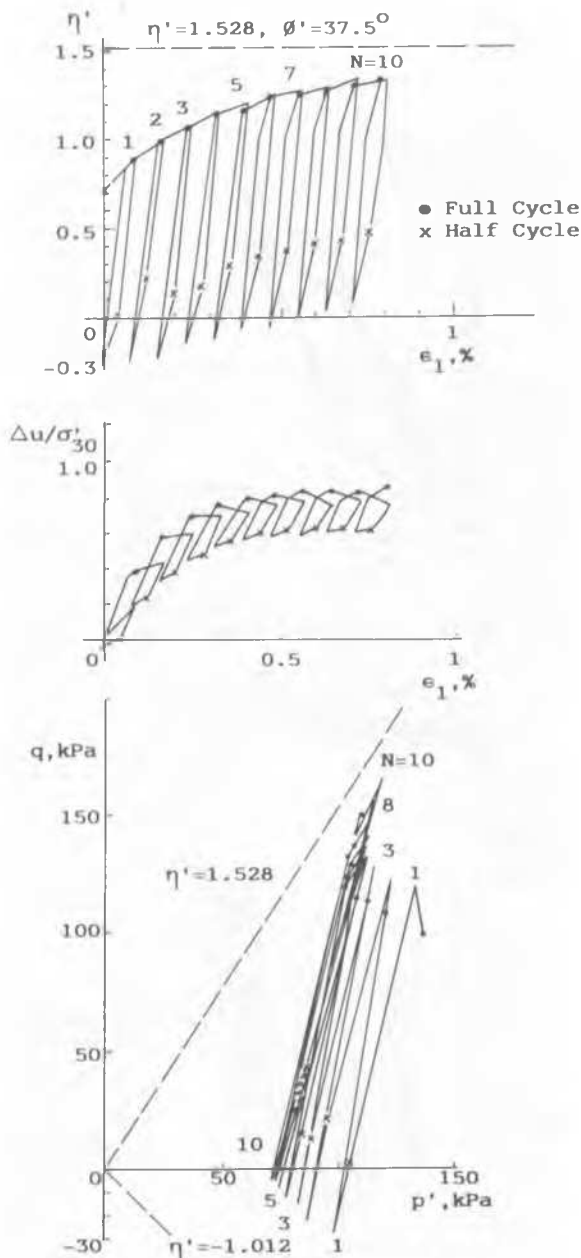


Fig.5. Stepped increasing cyclic strain test with $k'_0 = 2$.