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SYNOPSIS: The degradation behavior of soil may become important when considering the response of soft clay under cyclic loading condition. A nonlinear model was proposed by Idriss, et al. to account for the degradation behavior based on the controlled-strain test. By adopting a numerical procedure, the data obtained in controlled-stress cyclic triaxial test can be used to find the degradation parameter defined in the nonlinear degradation model proposed by Idriss, et al. A series of consolidated-undrained controlled-stress and controlled-strain cyclic triaxial tests were performed on laboratory manufactured normally consolidated soft clay samples. The relationship between degradation parameter and strain was determined based on data of controlled-stress test with the numerical procedure. The resulting values of degradation parameter versus strain from both controlled-stress test and controlled-strain test were compared.

INTRODUCTION

The modulus of soft clay will undergo degradation when loaded cyclically and with strain larger than some specific value. The effects of degradation may become significant and need to be taken into account in analyzing soil response under various cyclic loading condition. A nonlinear model was proposed by Idriss, et al.(1978) to account for this degradation behavior. The model was based on the results of laboratory cyclic triaxial test under controlled-strain loading condition and the Ramberg-Osgood equation was used to fit the initial backbone curve. However, it may be desirable and convenient to use controlled-stress test, especially when there is a need to impose an initial, sustained load prior to the cycling load. It is the purpose of this study to examine the applicability of the model to controlled-stress loading conditions and the difference in degradation behavior of normally consolidated clay between controlled-strain and controlled-stress test. In this study, a series of consolidated-undrained cyclic triaxial tests were conducted under both controlled-stress and controlled-strain loading condition. In order to avoid the influences of other factors, both the controlled-stress and controlled-strain tests were conducted under same effective confining pressure and loading frequency. The soil specimens used in this study were normally consolidated soft clays manufactured in laboratory. A numerical procedure was used to determine the parameters in the model developed by Idriss, et al. based on the data from controlled-stress cyclic triaxial test. Comparisons are then made between parameters thus derived and parameters determined using data from controlled-strain test.

DEGRADATION MODEL

The nonlinear model proposed by Idriss, et al. (1978) utilized an initial backbone curve to define the undegraded stress-strain response of soil and then the backbone curve was degraded by modifying the ordinate (stress) values to define the degraded responses. This modification is made according to a degradation model based on controlled-strain test data. The Ramberg-Osgood equation was used by Idriss, et al. to define the initial backbone curve. The soil degradation was represented in terms of the ratio of the secant Young's modulus on the Nth cycle, $(Es)_N$, to the secant Young's modulus in the first cycle $(Es)_1$, (the undegraded secant modulus), at the same strain. This ratio is defined as the degradation index, δ, and for a given controlled-strain test, the plot of the degradation index versus logarithm of number of cycles has a linear relationship. Thus, the degradation index is related to the number of cycles, N, by :

$$\delta = \frac{(E_s)_N}{(E_s)_1} = N^{-t} \tag{1}$$

where t is the slope of log δ - log N plot and represents a degradation parameter, t. The values of the parameter, t, increased as the strain increased, and a reasonably unique relationship between the parameter, t, and strain level has been found to exist by many researchers (Idriss, et al. 1978; Idriss, et al. 1980; Vucetic and Dobry, 1988; etc.).

In a controlled-stress test, the degradation index, δ_N , on any cycle, N, can be calculated using the undegraded backbone curve and the stress and measured strain on the given cycle. A Ramberg-Osgood equation was adopted to fit the data for the undegraded backbone curve. A simplified form of the equation was used, which can be expressed as :

$$\frac{\epsilon_c}{\sigma_d} = A + B\sigma_d^{R-1} \tag{2}$$

in which, ϵ_c is the axial strain, σ_d is the axial stress, and A, B, and R are the Ramberg-osgood parameters. Accordingly, at the end of the Nth cycle, the degradation index, δ_N , can be calculated, and for the N+1th cycle, the degradation index, δ_{N+1} , can be calculated. For a controlled-stress test, the measured strain varies with number of cycles and Eq. (1) does not apply. However, if the number of cycles N in Eq. (1) is replaced by an equivalent number of cycles, N', which is the number of cycles of uniform strain amplitude required to produce the degradation index, δ_N , at a strain amplitude equal to the actual amplitude on the N+1th cycle, then Eq. (1) can be expressed as :

$$\delta_N = N'^{-t} \tag{3}$$

and

$$\delta_{N+1} = (N'+1)^{-t} \tag{4}$$

where δ_N and δ_{N+1} , are the degradation indices from the controlled-stress test. Rearranging Eq. (3) to solve for N' and substituting the expression in term of $\delta_{f'}$ into Eq. (4) gives:

$$\delta_{N+1} = (\delta_N^{-\frac{1}{t}} + 1)^{-t} \tag{5}$$

With the degradation indices δ_N and δ_{N+1} , Eq. (5) can be solved for the degradation parameter, t, at the strain level of the N+1th cycle. Thus, the degradation parameter, t, can be calculated for each cycle in a controlled-stress test for the full range of strains encountered in the test. Because Eq. (5) can not be solved directly, an iterative procedure was used. A computer program was developed, which could fit the Ramberg-Osgood equation to the initial backbone curve and do the iteration for solving degradation parameter, t, from Eq. (5) (Lin, 1984).

SOIL SPECIMENS AND TESTING EQUIPMENT

The soil specimens used in this study were manufactured in laboratory by consolidating a kaolinite/water slurry in a one-dimensional consolidation apparatus. The vertical loads were applied in three stages to a final effective vertical stress of 64.1 kPa in soil. The kaolinite used for this purpose was obtained commercially in the form of a fine, white powder and is classified as CL according to the Unified Classification System. The specimen prepared using this procedure has an undrained strength of 9 kPa, which is a soft normally consolidated clay. After the last stage of the one-dimensional consolidation was completed, soil specimens were removed from one-dimensional consolidation apparatus and set up in a triaxial cell and consolidated isotropically to an effective confining pressure of 210 kPa. After consolidated in the triaxial cells, the specimens were then subjected to cyclic loading either in controlled-stress or controlled-strain condition.

The testing equipment used in this study is a CK e/p triaxial testing apparatus. The testing is fully computerized, and loading can be applied either in controlled-stress condition or in controlled-strain condition. An IBM personal computer was used for control and data reduction of the testing.

CONTROLLED-STRESS CYCLIC TRIAXIAL TEST

For the controlled-stress cyclic loading condition, a cycling period of 60 seconds and an effective confining pressure of 210 kPa were used. Ten sets of test were performed at different stress level for the determination of degradation parameter. Another four sets of test were performed for the purpose of implementing the initial backbone curve. The stress level is defined as the ratio of the cyclic deviator stress to the static undrained strength of the soil under the same effective confining pressure, which is 60 kPa.

The stress-strain data from the first cycle of loading were used to determine the initial backbone curve and the Ramberg-Osgood equation was fitted to the data. The data and resulting Ramberg-Osgood curve are shown in Fig. 1, the curve appears to fit the data very well. Part of the values shown in the initial backbone curve are higher than the static undrained strength of the soil, which may be caused by the much higher strain rate in cyclic test than that in static test.

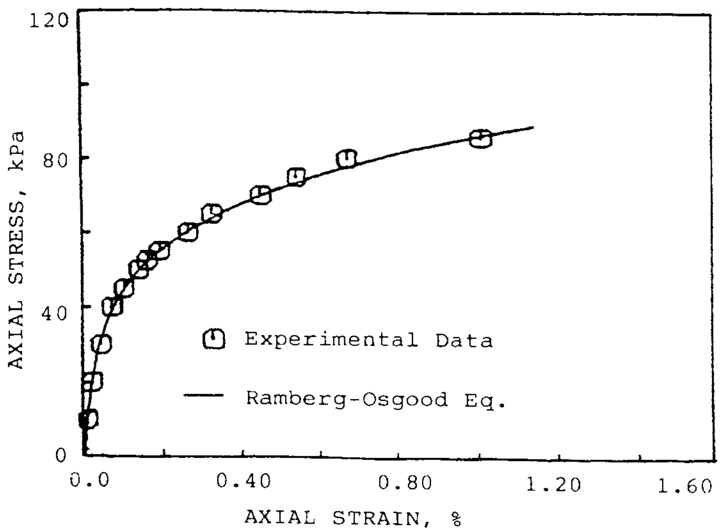

Fig. 1 The Initial Backbone Curve Based on the Data of Controlled-Stress Test

In each set of controlled-stress test, the degradation index, , at each strain value could be calculated as the ratio of the applied peak stress on the cycle divided by the peak stress determined from the undegraded backbone curve. A typical set of degradation index versus axial strain thus calculated is plotted in Fig. 2 for a stress level of 1.0. The degradation index decreases with increasing strain as shown in the figure. With the

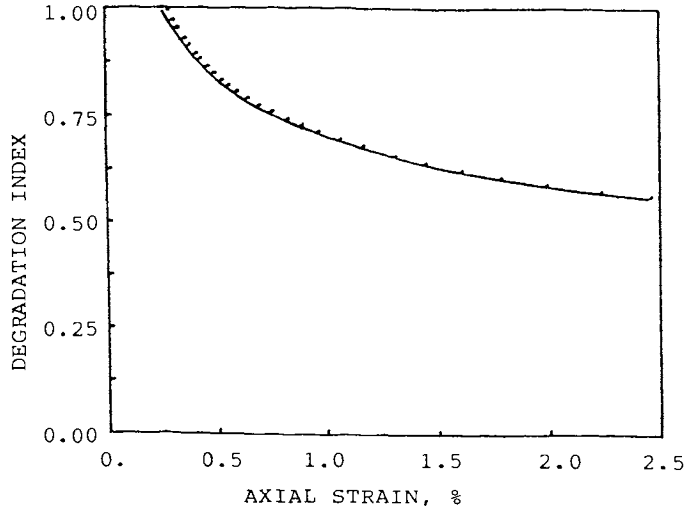

Fig. 2 Degradation Index versus Strain for Controlled-Stress Test with Cyclic Stress Level of 1.0

degradation indices, the values of degradation parameter versus strain were computed point by point using Eq. (5), and the results are shown in Fig. 3 for the stress level of 1.0. The computed degradation parameter increases as the strain increases. For all ten sets of controlled-stress test, the degradation parameters thus calculated are plotted versus axial strain together in Fig. 4. Although there are some scatters in Fig. 4, the values of the degradation parameter fall into a relatively narrow band and exhibit a same trend of

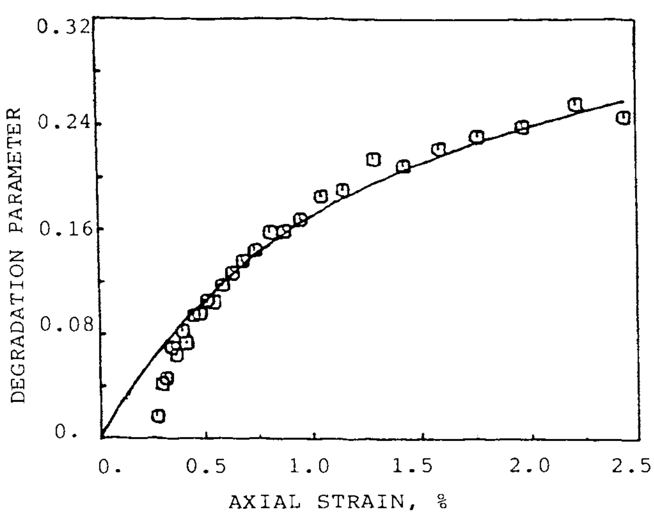

Fig. 3 Degradation Parameter versus Strain for Controlled-Stress Test with Cyclic Stress Level of 1.0

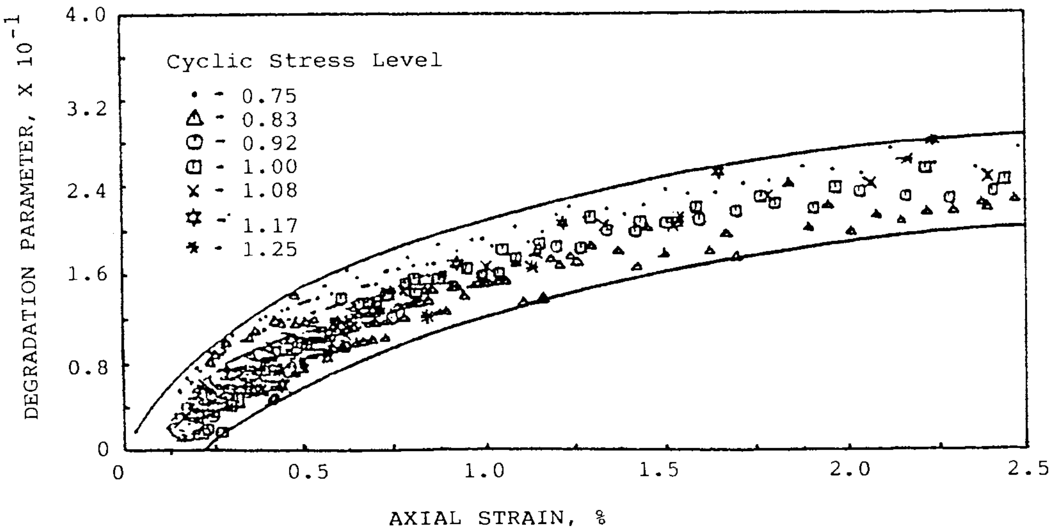

Fig. 4 Degradation Parameter versus Strain for Controlled-Stress Test

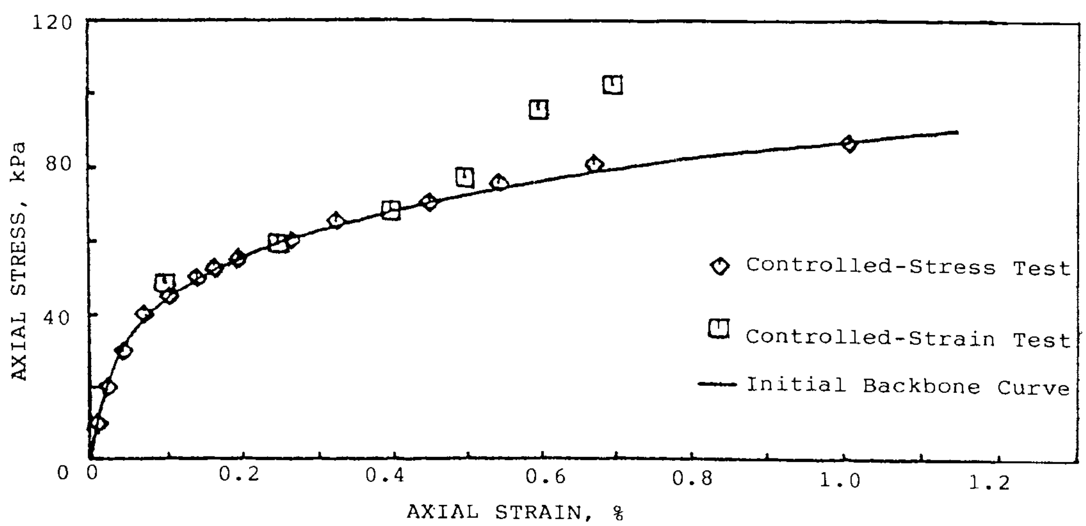

Fig. 5 The Initial Backbone Curve with Data of the Controlled-Strain Test

increase as the strain increases. The scatter in the degradation parameter may be caused by the usage of the numerical procedure and errors and uncertainty in measurements of strain. It was found that a small variation in strain can result in quite different values of degradation parameter during calculation.

CONTROLLED-STRAIN CYCLIC TRIAXIAL TEST

For the controlled-strain loading condition, six sets of test were performed with cycling period of 60 seconds and at different cyclic strain amplitude. The stress-strain data from the first cycle of loading were plotted together with the initial backbone curve determined using controlled-stress loading condition as shown in Fig. 5. The data from the controlled-strain test appear to fall on the same curve except for the last two points. The values of stress of the two points were higher than expected, which might due to the limitation of the equipment when strain amplitude became large. The initial backbone curve determined using controlled-strain test would be same as by the controlled-stress test as being expected.

The degradation index, δ , of each set of test was calculated as the ratio of the measured stress divided by the peak stress determined from the initial backbone curve at that strain amplitude. The computed degradation index were plotted in logarithm against the logarithm of the number of cycles as shown in Fig. 6 for all six sets of test. A linear relationship between the logarithm of the degradation index and the logarithm of the number of cycles appear to exist, and the slope of the straight line is the degradation parameter. The resulting degradation parameter is plotted against axial strain in Fig. 7. As shown in the figure, the value of degradation parameter increases as strain increases.

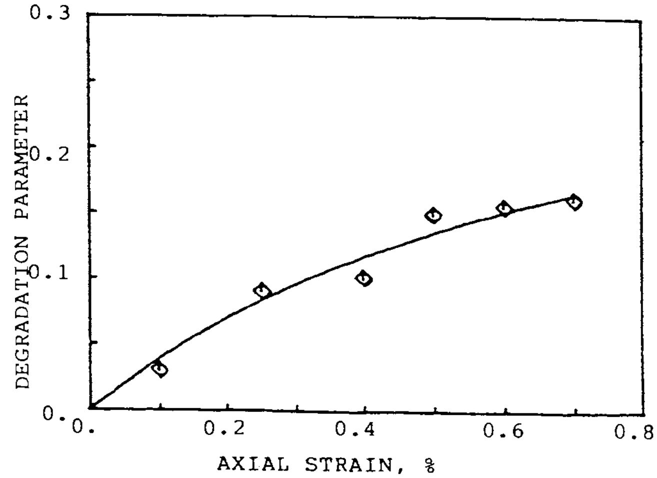

Fig. 7 Degradation Parameter versus Strain for Controlled-Strain Test

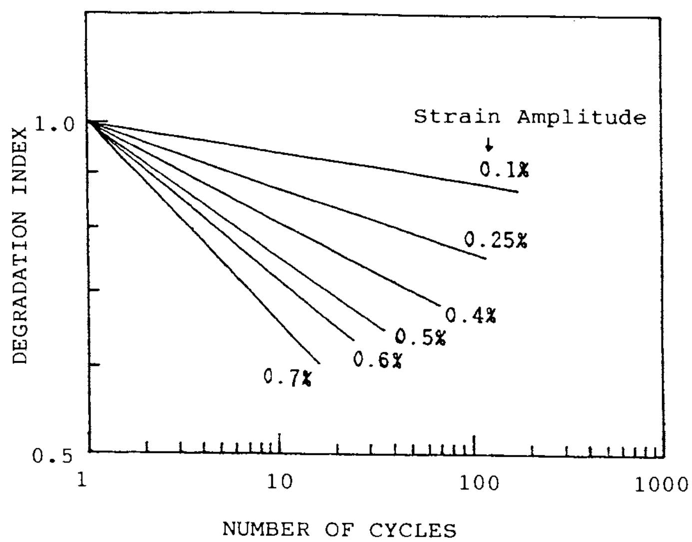

Fig. 6 Degradation Index versus Number of Cycles for Controlled-Strain Test

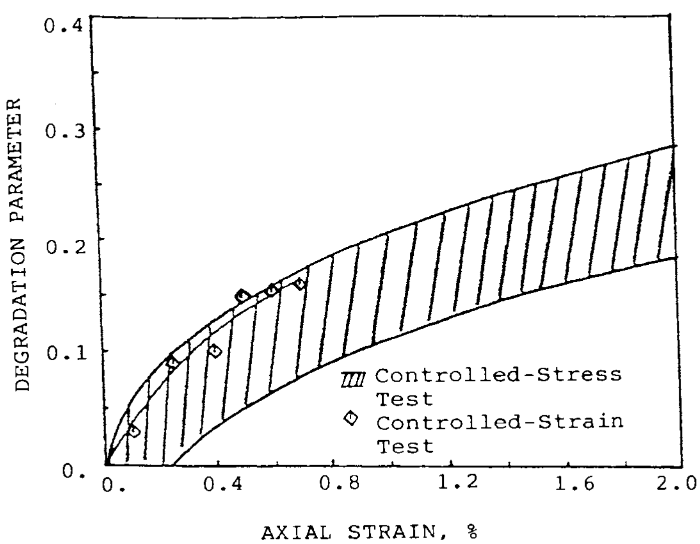

Fig. 8 Comparison of Degradation Parameters from Controlled-Stress Test and Controlled-Strain Test

In order to compare the degradation parameters obtained from the controlled-stress test and controlled-strain test, Fig. 4 is replotted with the data of degradation parameter in Fig. 7 as shown in Fig. 8. The degradation parameter derived from controlled-stress test was represented by a shaded narrow band. As observed in Fig. 8, the degradation parameter obtained from the controlled-strain test falls within the shaded band and is close to the upper limit of the band. The degradation parameters determined from both the controlled-stress and controlled-strain tests display a similar trend of increase with increasing strain. Although the values of computed degradation parameter versus strain based on controlled-stress test form a zone, the model proposed by Idriss, et al. appears to apply well. The relationship between degradation parameter and strain for a given soil may be a unique property.

CONCLUSIONS

By adopting a numerical procedure, the data obtained in controlled-stress cyclic triaxial test can be used to find the degradation parameter defined in the nonlinear degradation model proposed by Idriss et al. Both the controlled-stress and controlled-strain cyclic triaxial tests were performed on laboratory manufactured normally consolidated soft clay samples. The degradation parameters determined based on both controlled-stress test and controlled-strain test were compared. Conclusions drawn from this investigation are as follows.

1. The data of controlled-stress test can be used to find the degradation parameter defined in the degradation model proposed by Idriss, et al. by employing the numerical procedure described previously.

2. In general, the stress-strain data of the initial backbone curve from the controlled-stress test and controlled-strain test fall on the same curve, and the Ramberg-Osgood equation appears to fit the curve very well.

3. The resulting values of degradation parameter versus strain based on the data of controlled-stress test form a relatively narrow band. The scatters may be due to the shortcomings of the procedure and uncertainty in measurements of strain.

4. The degradation parameter determined directly using the data of controlled-strain test fall in the band of controlled-stress test and follow the same trend of increase with increasing strain. The nonlinear degradation model proposed by Idriss, et al. appears to apply well to controlled-stress test.

5. The relationship between degradation parameter and strain obtained from controlled-strain test coincided with that from controlled-stress test, and may be a unique property of a given soil.

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