Undrained cyclic shear behaviour of clay with initial static shear stress
M. Hyodo, Y. Yamamoto, M. Sugiyama
Department of Civil Engineering, Yamaguchi University, Ube 755, Japan

ABSTRACT

A series of undrained cyclic triaxial compression tests has been performed on a high plastic marine clay. Testing was performed for not only isotropically but also anisotropically consolidated specimens under various combinations of initial static and subsequent cyclic shear stresses. The cyclic shear strength was first discussed, and then, residual shear strain was investigated related with effective stress ratio at the peak of cyclic stress. Based on the experimental results, a semi-empirical model was proposed for evaluating the development of residual shear strain during cyclic loading. The model successfully explained the behaviour of clay subjected to various magnitude of initial static and subsequent cyclic shear stresses.

INTRODUCTION

The main interest about the design problem against earthquake has been focused on liquefaction of saturated sands. Clays have been considered to be rather stable than sands during earthquake. However, serious damages of structures based on thick clay layers were reported in 1985 Mexico Earthquake (Seed et al. [6], Mendoza et al. [2]). A large deformation of ground due to amplification of seismic motion is recognized as a characteristic of clay behaviour during earthquake. Additionally, a lot of collapses of fills were caused by failure of clay base layers in 1964 Niigata Earthquake, 1978 Miyagiken-oki Earthquake and 1983 Nihonkai-chubu Earthquake in Japan.

On the other hand, in the design of offshore platform against wave loading, the cyclic properties of clays have been investigated and taken in the practical design method (Andersen et al. [1]). Although the
dynamic problem of clays has not been investigated so seriously as a liquefaction of sands, hereafter a lot of dynamic problems about clays will arise with developing the construction of various structures based on the clay layers.

A series of undrained cyclic triaxial tests has been performed on plastic marine clay in this study. Testing was carried out under various combinations of initial static and cyclic shear stresses which are expected in the soil elements subjected to cyclic loadings in the vicinity of structures. The tests were carried out on not only undisturbed but also reconsolidated specimens. Further, based on the experimental results, a semi-empirical model for predicting residual shear strain developed during cyclic loading is proposed which will be a useful tool for practical design methods.

TESTING PROCEDURE

Cyclic triaxial compression tests were carried out on both undisturbed and reseaded marine clay named Itsukaichi clay which was sampled at the south coast of Hiroshima in Japan. Its index properties are $G_s=2.532$, $w_L=124.2\%$, $w_p=51.4\%$ and $I_p=72.8$. In order to prepare the reseaded sample, the clay slurry mixed with an initial water content of 260% was poured into a consolidation vessel and was then preconsolidated by a vertical pressure of 50kPa. Then the specimens with initial dimensions of 50mm in diameter and 100mm in height were trimmed from the clay block formed by consolidation vessel. The specimens were initially consolidated isotropically and then consolidated anisotropically by applying a static deviator stress until the constant mean principal stress of 200kPa in the triaxial cell.

A sinusoidal cyclic axial load was applied at a frequency of 0.02Hz which was decided after investigating the homogeneity of generating the pore pressure in the specimen under undrained cyclic loading. Cyclic loading tests were performed over a range of initial static deviator stress $q_s$ varying from 0 to 240kPa at 60kPa intervals for normally consolidated specimens. From four to six magnitudes of cyclic deviator stress $q_{cyc}$ were combined with each static deviator stress so that both reversal and non-reversal of cyclic shear stresses were simulated.

COMPARISON BETWEEN UNDISTURBED AND RESEADEMENTED CLAYS

In order to compare the cyclic behaviours between undisturbed and reseaded samples, undrained cyclic triaxial tests were performed on both specimens which were normally consolidated at 200kPa. Fig.1 shows the relationship between cyclic deviator stress ratio and number.
of cycles required to cause 10% double amplitude of axial strain, DA, which is considered to be a failure condition. As shown in Fig. 1, there is not so remarkable difference between undisturbed and resedimented samples. Then the results of resedimented samples are used for the following discussions.

CYCLIC BEHAVIOUR OF NORMALLY CONSOLIDATED CLAY

The cyclic triaxial tests were performed considering both reversal and non-reversal of cyclic shear stresses. Typical effective stress paths during cyclic loading for normally consolidated clay in each loading pattern are presented in Fig. 2. The failure envelopes obtained from undrained monotonic tests are also drawn in each figure. The slopes of the envelopes for compression and extension are $M_c=1.560$ and $M_e=1.456$, respectively. In the isotropically consolidated result, as shown in Fig. 2 (a), the effective stress path moved towards the failure envelopes during cyclic loading and finally it traced a steady loop which reached the failure envelopes on both compression and extension sides. Pore pressure measured at the bottom of specimen through pedestal did not develop up to the initial confining stress. On the other hand, in the anisotropically consolidated results, as shown in Fig. 2 (b) and (c), the effective stress paths moved until the upper end of them touched the failure line on the compression side. Further, it is found that the stress paths crossed the failure envelopes at the final stage of cyclic loading. This phenomenon was also observed by Hyde and Ward [3] and was explained that samples became more heavily overconsolidated under undrained conditions. Although there is some extent of stress reversal from compression to extension side in the result of Fig. 2 (b), failure mode is almost same with the non-reversal case shown in Fig. 2 (c).

Typical results demonstrating the relationship between cyclic deviator stress and axial strain are presented in Fig. 3. A large amplitude of cyclic axial strain was observed in the isotropically consolidated result as shown in Fig. 3 (a). The behaviour looks similar with that of sand when the liquefaction is achieved. On the other hand, the residual strain was predominant in the anisotropically consolidated results as shown in Figs. 3 (b) and (c). Furthermore, it should be noted that residual strain during a cycle triggered to increase when the stress paths approached the critical state line.

CYCLIC SHEAR STRENGTH

It is convenient to make a unified definition of cyclic shear strength in both reversal and non-reversal stress conditions. Taking 10% peak axial strain, PS, as a failure criterion in both reversal and non-reversal regions, the relationship between cyclic deviator stress ratio and
number of cycles required to cause failure for each initial static deviator stress $q_s$ is represented as shown in Fig.4. Further, the variation of cyclic deviator stress ratio required to cause PS=10% in 20 cycles with initial static deviator stress ratio is summarized in Fig.5. It is found in both figures that the cyclic deviator stress ratio to cause failure decreases with increasing initial static deviator stress. Defining the cyclic strength as $R_l=\{(q_{cyc}+q_s)/p_c\}_l$, they can be approximated by straight lines in logarithmic form. These are given by parallel straight lines for each initial static deviator stress as shown in Fig.6 in which the cyclic strength for $q_s/p_c=0$ is also illustrated and formulated by the following equation. The variations of cyclic strengths in 5, 20 and 100 cycles with initial static deviator stress ratio are illustrated in Fig.7, respectively.

$$R_l=\{(q_{cyc}+q_s)/p_c\}_l = \kappa N^\beta$$ \hspace{1cm} (1)

where $\beta=-0.088$ and $\kappa=1.0+1.5q_s/p_c$.

EVALUATION OF CUMULATIVE AXIAL STRAIN DURING CYCLIC LOADING

Attempts were made to quantify the maximum axial strain corresponding to the peak cyclic stress on the compression side in each loading cycle. The peak axial strains $\varepsilon_p$ from all tests were related using an effective stress ratio $\eta_p (=q_s/p)$ which is the value of peak deviator stress divided by mean effective principal stress of each peak cyclic stress. Fig.8 is the relationship between peak axial strain and effective stress ratio. It is recognized in the figure that there is a unique relationship between peak axial strain and effective stress ratio although the magnitude of initial static and applied cyclic deviator stresses are different one another. Furthermore, it is found in these figures that although the start points are different for each initial static deviator stress, the main part of the relations are approximated by a unique hyperbola as the following equation.

$$\varepsilon_p = \eta_p/(2.0-\eta_p)$$ \hspace{1cm} (2)

RELATIVE EFFECTIVE STRESS RATIO AND CYCLIC SHEAR STRENGTH RATIO

In the previous section, a unified cyclic shear strength, $R_l=\{(q_{cyc}+q_s)/p_c\}_l$, applicable to all the loading patterns was defined. In order to represent the undrained cyclic behaviour of clay, let us introduce the following two parameters. The first parameter defined is an index showing the possibility of cyclic failure, $R/R_l$, which is the ratio of an peak cyclic deviator stress, $R=q_s+q_{cyc}$ to cyclic shear strength in a given number of cycles. $R/R_l$, named cyclic shear strength ratio, is equivalent
Soil Dynamics and Earthquake Engineering 303

to a reciprocal of the safety factor against cyclic failure. When the magnitude of \( R \) is constant, \( R/R_i \) increases with increasing the number of cycles and caries from zero at non-loading to unity at the failure.

For another parameter, we define:

\[
\eta^* = \frac{(\eta_p - \eta_s)}{(\eta_i - \eta_s)}
\]  

(3)

where \( \eta_p \) is an effective stress ratio at the peak of cyclic stress in each cycle, \( \eta_s \) is the effective stress ratio of initially consolidated condition and \( \eta_i \) is the effective stress ratio at the failure. This parameter, \( \eta^* \), indicates the relative effective stress ratio between initial point and final point in \( p-q \) space as shown in Fig.9. These parameters are originally introduced for sand by Hyodo et al. [4] and also applied to the isotropically consolidated clay (Hyodo et al. [5] 1992). By correlating the values of both parameters, we obtain Fig.10 for each \( q_s/p_s \). The best fit curve for each relation is given by a unique curve formulated as the following equation in spite of the difference of initial static and subsequent cyclic deviator stresses.

\[
\eta^* = \frac{R/R_i}{(a-1)R/R_i}
\]  

(4)

where \( a \) is obtained as 6.5 by the experiments.

Cyclic-induced peak axial strain is calculated by the following process.

1. Cyclic shear strength, \( R_i \), for the desired initial static deviator stress and number of stress cycles is decided through the relationship given by Eq.(1). Then the cyclic shear strength ratio \( R/R_i \) is obtained by dividing the applied stress ratio \( R \) by the strength \( R_i \).

2. The relative effective stress ratio \( \eta^* \) is obtained by substituting \( R/R_i \) into the relationship between \( \eta^* \) and \( R/R_i \) given by Eq.(4).

3. The effective stress ratio \( \eta_p \) at the peak cyclic stress of a given stress cycle is calculated by the following rewritten form of Eq.(3).

\[
\eta_p = \eta^* (\eta_i - \eta_s) + \eta_s
\]  

(5)

4. The peak axial strain is evaluated by substituting \( \eta_p \) into Eq.(2).

These steps should be continued from the first to the end of stress cycle. The predicted and experimental peak axial strains are presented in Fig.11. Fairy good correspondences are observed between predicted and experimental results in spite of very complicated initial conditions. Therefore, it is confirmed that the proposed model is a
reasonable method for accumulating the cyclic–induced shear strain of clay subjected to various magnitude of initial static and subsequent cyclic shear stresses.

CONCLUSIONS

In order to evaluate the cyclic shear strength and deformation of clay with initial static shear stress, a series of cyclic triaxial tests was performed. A semi–empirical model for accumulating the cyclic–induced axial strain was proposed. The model can evaluate the residual shear strain of clay with various magnitude of initial static shear stress.

REFERENCES


Figure 1 Comparison between cyclic strengths of undisturbed and resedimented samples
Figure 2: Effective stress paths in the cases of, (a): isotropically consolidated, (b): anisotropically consolidated with stress reversal, (c): anisotropically consolidated with non-reversal
Figure 3 Relationships between deviator stress and axial strain in the cases of, (a): isotropically consolidated, (b): anisotropically consolidated with stress reversal, (c): anisotropically consolidated with non-reversal

Figure 4 Relationship between cyclic deviator stress ratio $\frac{q_{cy}}{p_c}$ and number of cycles to cause peak axial strain $PS=10\%$
Figure 5 Relationship between normalized cyclic deviator stress and initial static deviator stress to cause PS=10% at 20 cycles.

Figure 6 Relationship between cyclic deviator stress ratio \( \frac{q_{ cyc } + q_s}{p_c} \) and number of cycles to cause peak axial strain PS=10%.
Figure 7  Relationships between cyclic strength $R_c$ and initial static deviator stress ratio to cause PS=10% at 5, 20, 100 cycles

Figure 8  Relationship between accumulated peak axial strain and effective stress ratio
Figure 9  Schematic diagram for relative effective stress ratio
\[ \eta^* = \frac{\eta_p - \eta_s}{\eta_f - \eta_s} \]

Figure 10  Relationship between relative effective stress ratio \( \eta^* \) and cyclic shear strength ratio \( R/R_f \)

Cyclic strength ratio  \( R/R_f \)

Figure 10  Relationship between relative effective stress ratio \( \eta^* \) and cyclic shear strength ratio \( R/R_f \)
Soil Dynamics and Earthquake Engineering

(a)

(b)
Figure 11 Predicted and experimental accumulated peak axial strain