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EARTHQUAKE INDUCED SETTLEMENTS IN CLAYS

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SUMMARY

When the excess pore pressures which are generated during the earthquakes, the sttlements of grounds take place due to decrease of volume of the voids. In the case of clays, the recompression settlements after cyclic loading continue over a long time and the amount of settlements are more pronounced than in sands. Even if the soil is not failed or pore pressure does not develop equal to the effective confining pressure, the dissipation of excess pore pressure may lead to harmful settlement. The object of this study is to investigate the fundamental nature of volume change in post-cyclic recompression process on clays and find a clue to solve the quantity and duration of settlement of clay subjected to earthquake force.

INTRODUCTION

When the soft clay grounds are subjected to cyclic loads induced by such as seismic, traffic, offshore-wave load and so on, they might induce harmful settlements. There have been several cases that structures or embankments constructed on clays caused abnormal settlements after the earthquakes (Ref.1) or beginning of travelling the motor vehicles (Ref.2). Cyclic loads in grounds produced by earthquakes continue in fairy short term, whereas a winter storm in the sea subjects offshore structures to cyclic loads that may last several days, and traffic loads induce that loads in very long term. Therefore, it is considered to be almost undrained condition in short-term cyclic shearing, on the other hand, in long-term shearing, it is supposed to be in partial drained condition in which generation and dissipation of pore pressure develop simultaneously, that is, in the former, dissipation occurs especially after shaking and in the latter, dissipation continues during cyclic loading. The main scope of the present study is to investigate the nature of volume change of clay subjected to various cyclic shear stresses. At the same time, an analytical model is pursued for presenting the generation and dissipation of pore pressure and volumetric change of clays under cyclic shear conditions.

MECHANISM OF CLAY'S SETTLEMENT UNDER CYCLIC SHEAR LOADING AND TEST'S PROCEDURE

Deformation of clay under cyclic loading with inclusion of drainage may constitute: 1) shear deformation under undrained cyclic loading 2) volumetric change due to dissipation of cyclically induced pore pressure. The schematic diagram for explaining this behaviour is shown in Fig.1. The total deformation

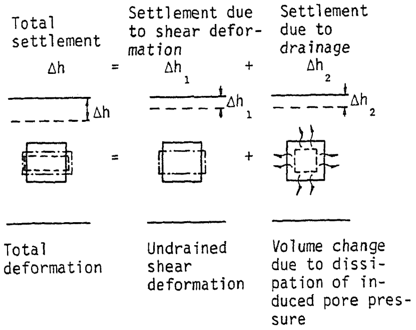


Fig. 1 Schematic diagram for explaining the settlement of ground due to cyclic loading

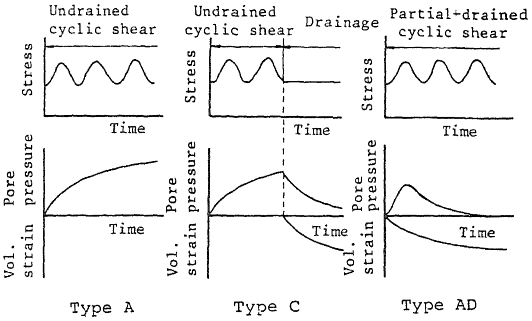


Fig. 2 Three types of cyclic triaxial tests performed in this study

is evaluated by combination of these two factors. When evaluating the one dimensional ground's settlement due to horizontal shaking of earthquake, the second factor is predominant. However, it is considered to be important to evaluate both factors in the general problems of cyclic loadings. In order to investigate these factors individually, the following three types of cyclic triaxial tests as shown in Fig.2 were carried out.

1) Undrained cyclic triaxial tests (type-A).
Results from this type of test were used to estimate the pore pressure and residual shear strain.

2) Undrained cyclic triaxial tests followed by drainage (type-C).
In this type of test, drainage is permitted after a certain number of load cycles is applied to the specimen and the coefficients of volume compressibility and permeability were determined from measurement of volume change of specimen due to cyclically induced pore presuure.

3) Drained cyclic triaxial tests (type-AD).
The cyclic load is applied to a specimen under drained condition by opening the drainage system. It was performed in order to investigate the deformation of clay under long-term cyclic shear condition and that situation will not occur in short-term cyclic loading such as earthquake. Throughout the cylindrical specimen (3.5cm in diameter and 8.75cm in height) in triaxial cell, distribution of pore pressure is not homogeneous during drained cycling because of low permeability of clay. In this sense, this type of cyclic test can be classified as a partial-drained shear test.

Reconstituted highly plastic clay called "Ariake Clay" was used in these tests. Index properties and some mechanical parameters are: $G_s = 2.65$, $w_L = 123\%$, $I_p = 69$, $C_c = 0.700$, $C_s = 0.163$ and $\phi' = 39°$. The clay cylinder was trimmed as a specimen for every triaxial test from the clay block which was fully preconsolidated under 59kPa of vertical pressure in the large consolidation vessel. The water content was 90 to 95% on the average.

Pore pressure was measured through the porous stone with 3mm in diameter buried in the center of lower pedestal. Drainage was done from the side wall around the lower pedestal through the drain paper surrounding the sprcimen. The cyllindrical specimens for the triaxial tests were isotropically preconsolidated for 24hrs under the confining pressures of 100, 200 and 300kPa. Then cyclic loading started after isotropic consolidation. In order to investigate the effect of duration of cyclic loading on following volume change of clay, the following two types of cyclic loadings were applied, that is, short-term cycling, two-way loading in both compression and extension sides, and long-term cycling, one-way loading in compression side. The effect of change of principal axis's direction will be also obvious from this investigation. The maximum numbers of load cycles were 500 for two-way loading and 3600 for one-way loading.

FORMULATION OF GENERATED PORE PRESSURE IN UNDRAINED CYCLIC TRIAXIAL TEST

The pore pressures in one-way and two-way loadings were measured in undrained cyclic triaxial tests. They depend on confining pressure and intensity of cyclic loading. It is, therefore, assumed that the pore pressure ratio can be formulated as a function of the stress ratio and the number of load cycles. Regression analyses for these formulations were performed and the following relations were obtained.

$$u/\sigma_c = 0.867(\Delta\sigma_a/2\sigma_c)^{1.986}N^{0.385} \qquad \text{(two-way loading)} \qquad (1)$$

$$u/\sigma_c = 0.171(\Delta\sigma_a/2\sigma_c)^{1.418}(\log 10N)^{1.535} \qquad \text{(one-way loading)} \qquad (2)$$

Figs.3, 4 show the variations of pore pressure ratio with number of load cycles; Fig.3 for two-way loading, Fig.4 for one-way loading, respectively. All of the observed values are compared with the regression curves given by eqs.(1), (2). The coefficients of correlation resulted from the regression analyses were 0.94-0.95 which may be considered to be a fairly high value. It is also recognized from the observation of Figs.3, 4 that the prediction curves calculated by the empirical equations are in good agreement with the experimental results.

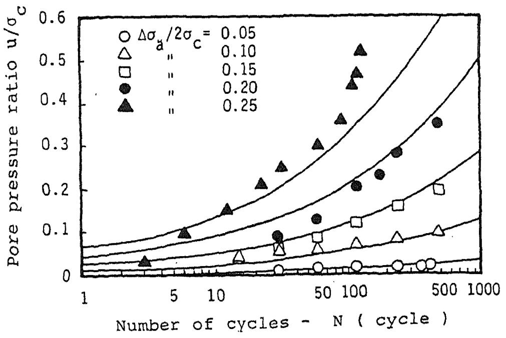


Fig. 3 Pore pressure versus number of load cycles in two-way cyclic loading

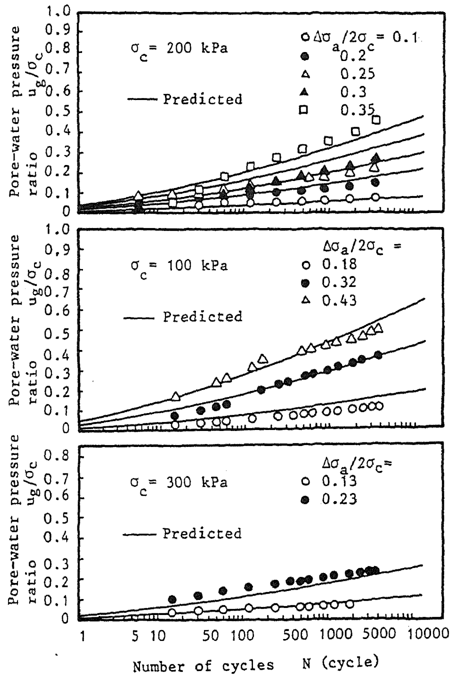
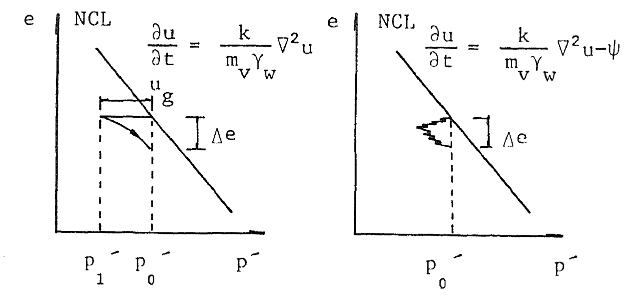


Fig. 4 Pore pressure versus number of load cycles in one-way (comp. side) cyclic loading

VOLUME CHANGE DUE TO DISSIPATION OF INDUCED PORE PRESSURE

When drainage of cyclically induced pore pressure take place, recompression settlements will occur. As mentioned previously, an element of clay ground may sometimes be situated under partial drained conditions in which the sequence of



(a) Post-cyclic recompression

(b) Partial-drained cyclic loading

Fig. 5 State pathes in post-cyclic recompression and partial-drained cyclic loading

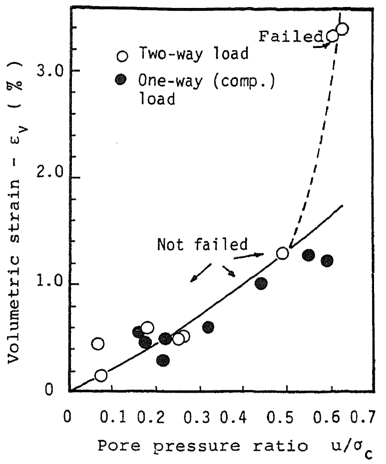
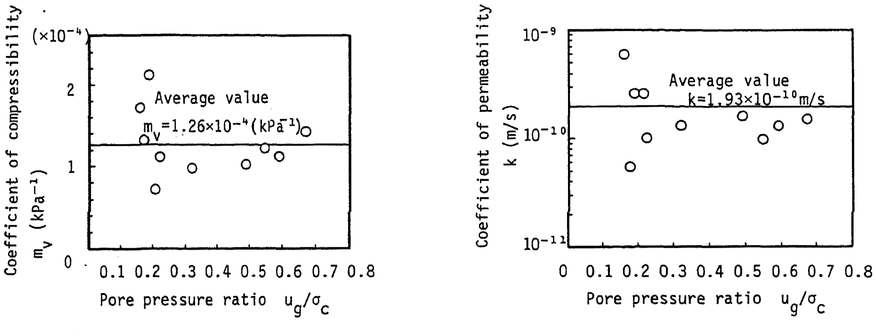


Fig. 6 Relationship between recompression volumetric strain and induced pore pressure

pore pressure build-up and its dissipation is repeated. It should be investigated only under long-term cyclic loading conditions, while, because of low permeability of clay, it is regarded as undrained in case of short-term cyclic loading conditions such as an earthquake. In this study, a unified procedure for representing both cyclic loadings is tried to develop. The post-cyclic recompression tests were carried out to investigate the characteristics of volume change and to get the coefficients of compressibility and permeability in drained sequence. The interrelation between undrained cyclic loading with drainage and partial-drained cyclic loading is compared in Fig.5 by the e-logp plots.

Fig.6 shows the results of post-cyclic recompression test which is the relationship between volumetric strain developed by dissipation of induced pore pressure and residual pore pressure generated in undrained cyclic shear. It is recognized that there exists a unique relationship between pore pressure and volumetric strain in spite of the differnce of way for cyclic loading, one-way and two-way. However, it is found in this figure that there is a great difference in the volumetric strain whether the specimens were failed or not. The volumetric strain becomes larger gradually with the magnitude of induced pore pressure and suddenly increases when specimen reaches cyclic failure. The coefficients of compressibility and permeability were determined by log t method of



(a) Coefficient of compressibility (b) Coefficient of permeability

Fig. 7 Coefficients obtained by post-cyclic recompression tests time-recompression curve. The observed values of those coefficients are illustrated in Fig.7. Those coefficients in the figure are on the specimen of non-failure and the plot for failure is not presented. Although the number of data is limited and the plots are somewhat scattering, it can be said that those two factors are kept constant independent of the cyclically induced pore presuure ratio.

FINITE ELEMENT ANALYSIS EVALUATING GENERATION AND DISSIPATION OF PORE PRESSURE

Numerical analysis of pore pressure build-up and its dissipation was carried out by extension of Booker et al's method which was originally introduced in the liquefaction problem in sand (Ref.3). The governing equation is

$$\{\nabla\}^T[K]\{\nabla\frac{u}{\gamma_w}\} = m_v\{\frac{\partial u}{\partial t} - \frac{\partial u_g}{\partial t}\} \qquad (3)$$

in which [K]: permeability matrix, ug: cyclically induced pore pressure. Numerical analysis using the finite element method were conducted for the clay cylinder in triaxial tests. A sketch of specimen and its finite element model are presented in Fig.8. The boundary condition which is to be zero pore pressure is given in the side boundary of specimen. Since only the radial flow is permitted in this case, the finite element model can be replaced by the simpler one which is shown in Fig.8c.

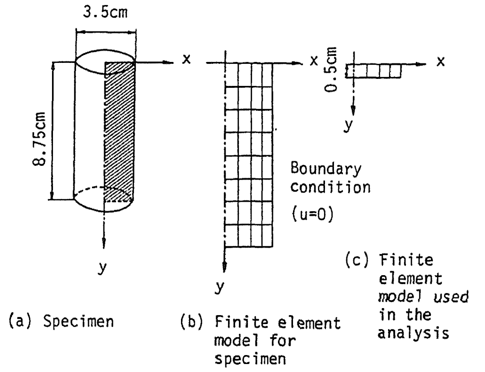


Fig. 8 Finite element model for specimen in cyclic triaxial test

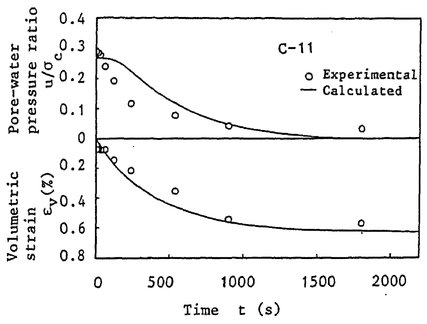


Fig. 9 Observed and calculated pore pressure and volumetric strain in post-cyclic recompressiontest

Fig.9 shows observed and calculated results of post-cyclic recompression test. Cyclically induced pore pressure calculated by eqs.1, 2 are given to the governing equation (eq.3) as an initial condition and solution is performed with zero genration term. Fig.10 presents the behaviour of partial-drained cyclic shear condition. In this case eqs.1, 2 are substituted into the second term of eq.3. It is recognized from these results that observed and numerical results are in good correspondence, each other. Therefore, it can be said from these comparison that the proposed model is appropriate for analysis of cyclic loading with inclusion of drainage.

CASE STUDY FOR EVALUATING EARTHQUAKE INDUCED SETTLEMENT OF CLAY

The cross section, as shown in Fig.11 is the object of analysis for a case

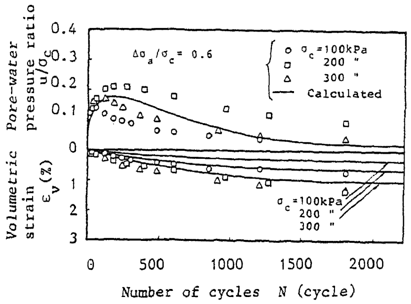


Fig. 10 Observed and predicted behaviour of drained cyclic shear tests

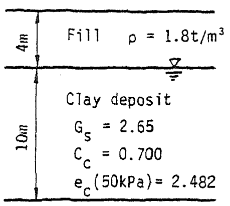


Fig. 11 Soil profile analyzed

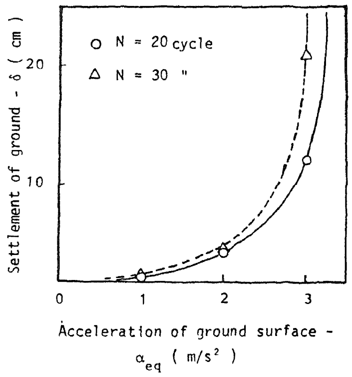


Fig. 12 Analyzed settlement of ground applying various acceleration

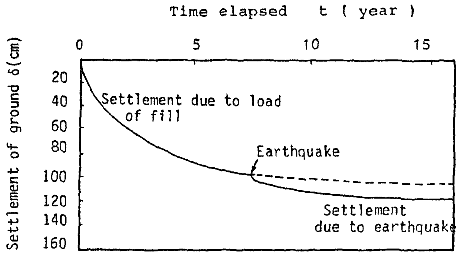


Fig. 13 Relationship between settlement of ground and time elapsed since the start of loading of fill

study. It is assumed that an earthquake has happened at almost end of consolidation by the fill's dead load. A simplified method proposed by Iwasaki et al (Ref.4) was used in order to evaluate the shear stresses induced by earthquake. In this method, the shear stress at the arbitrary depth in the soil is calculated by taking the acceleration of ground surface. The surface accelerations were taken to be 1, 2 and 3m/s^2, and the number of load cycles to be 20 and 30 cycles, respectively. Generated pore pressures were calculated by eq.(1) in these conditions. The finite element analysis was performed on the clay deposit and the boundary condition (u=0) was applied to the both sides of top and botom of clay layer. Fig.12 shows the final settlement of ground ,in which it is found the settlement increases rapidly with the increase of acceleration. Fig.13 presents the settlement versus time elapsed since the construction of fill.

CONCLUSIONS

The fundamental natures of volume change in post-cyclic recompression process subjected to short and long-term cyclic loadings were investigated. The tests' results showed that the volume changes are dependent on magnitude of generated pore pressure in undrained process but are not dependent on the way of loading and duration of cyclic loading. The volume changes during and after cyclic loadings were given by combination of the consolidation equation with the formulated pore pressure.

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