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SETTLEMENT AND EXCESS PORE WATER PRESSURE OF SATURATED CLAY INDUCED BY CYCLIC SHEAR WITH DIFFERENT PERIODS

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SUMMARY

For normally consolidated specimens, two-way strain controlled cyclic simple shear tests with different periods are carried out under the undrained conditions, and subsequently the excess pore water pressures induced by cyclic shear are dissipated. Then effects of the period of cyclic shear on the generation of the excess pore water pressure and on the settlement induced by the dissipation of the excess pore water pressure are investigated. It is clarified that the periods of cyclic shear have considerable effects upon the generation of the excess pore water pressure, and that the settlement of clay layers are hardly influenced by them.

INTRODUCTION

In the case that a soft clay layer is subjected to seismic cyclic shear, the excess pore water pressure is produced and by the dissipation of the accumulated excess pore water pressure, the ground subsidence may occur. Such a settlement of a clayey layer has been confirmed in the 1957 Mexico Earthquake (Ref. 1), in the 1978 Miyagiken-oki Earthquake (Ref. 2), and in the 1985 Mexico Earthquake (Ref. 3). Especially, it has been reported that in the Mexico Earthquake on 1957, immediately after the earthquake the ground settled considerably and the rate of the settlement increased and that in the Mexico Earthquake on 1985, the structures settled about 3.8cm.

In the laboratory, it has been observed from the cyclic simple shear test results that not only for the normally consolidated clay layers but for the overconsolidated ones, the settlement, which depends on the seismic excess pore water pressure and the overconsolidation ratio, occurs (Ref. 4).

As for the effects of periods on the dynamic property of a clay, Matsui et al. (Ref. 5) observed that for a given number of cycles, higher excess pore water pressures are generated at lower frequencies by using the stress-controlled triaxial test equipment. Procter et al. (Ref. 6) clarified the effects of frequency on the cyclic stress ratio causing a certain strain. Brown et al. (Ref. 7) used a frequency of 10Hz for their studies on the stress-strain characteristics of silty clay, based on the indication by Lashine (Ref. 8) in which there is no frequency effect over the range from 0.01Hz to 10Hz. Further, Fisher et al. (Ref. 9) observed that cyclic shear strength of clays obtained in tests with high frequency loading(1Hz), are significantly greater than those obtained from tests with low frequency loading(1/15Hz). These researches, however, are mainly related to the dynamic shear strength of clay and there are many unknown factors such as effects of the periods on the generation of excess pore water pressure, the settlement and so on.

So, in this paper, for normally consolidated specimens, two-way strain controlled cyclic simple shear tests with different periods are carried out under the undrained conditions, and followed by the dissipation of the excess pore water pressure induced by cyclic shear. Then the effects of period of cyclic shear on the generation of the excess pore water pressure and on the settlement of clayey layers are investigated.

SAMPLE AND SPECIMENS

The sample used in this study is kaolinite clayey powder. The specific gravity G_s of this sample is 2.70, the liquid limit w_L is 53.5%, and the plastic limit w_p is 28.5%.

The specimens were prepared as follows: the clayey powder was mixed with the de-aired water to make a slurry with the water content of about 80%. After keeping the water content constant for one day, the slurry was de-aired in the vacuum cell for about half an hour, and then poured into a rubber membrane placed in the shear box of the simple shear test apparatus. The slurry was pre-consolidated under the vertical stress of 49kPa and the consolidation duration was 22 hours. The prepared specimens were like a disk in shape and 75mm in diameter, 20mm in height.

TEST PROCEDURE

The apparatus used in this study is the dynamic simple shear test device (Ref. 4). The cyclic shear strain was applied to the specimen, using the servo-controlled electro-hydraulic unit.

A specimen normally consolidated under the vertical stress σ'_{vo} was subjected to undrained cyclic shear with a strain amplitude γ_{dyn} which varied in the range from 0.05%-3.0%. The number of cycles n took the value 200. The wave form of the cyclic shear strain was sinusoidal (two way cyclic strain) and the periods were 0.2s, 0.5s, 2.0s and 10.0s. Further, in these series of tests, the special cases were also included; in which the

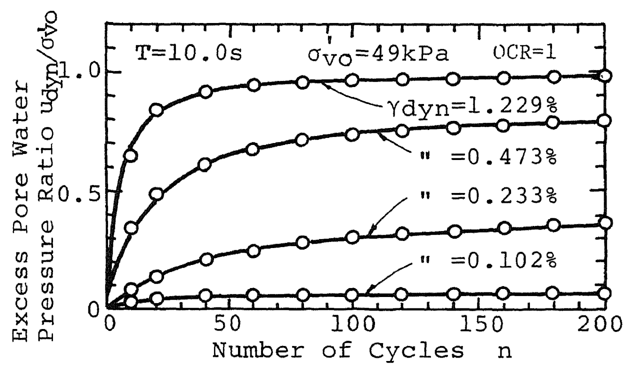

Fig.1 Excess Pore Water Pressure Induced by Cyclic Shear, T=10s.

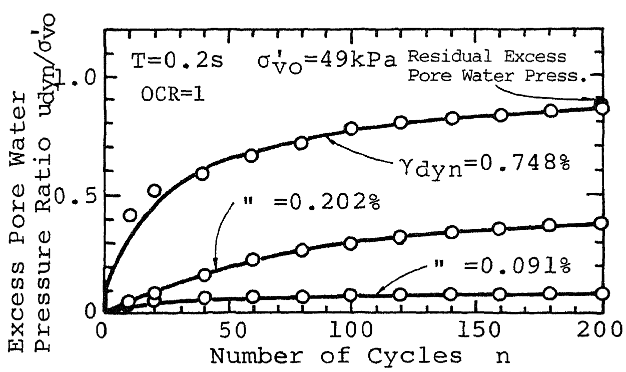

Fig.2 Excess Pore Water Pressure Induced by Cyclic Shear T=0.2s.

number of cycles n and the cyclic shear strain amplitude γ_{dyn} were kept constant as 50, 2.2%, respectively, but the periods of cyclic shear were varied.

During the cyclic shear tests, the horizontal displacement, shear resistance and the pore water pressure were measured. Subsequently, the drainage from the top of the specimen was permitted and then the settlement and the pore water pressure at the base of the specimen were measured with time.

EFFECTS OF PERIOD ON THE EXCESS PORE WATER PRESSURE

The relationships between the excess pore water pressure ratio u_{dyn}/σ'_{vo} and the number of cycles n for the periods of 10.0s and 0.2s are shown in Figs.1 and 2, respectively. It is seen from these figures that the smaller the periods of cyclic shear, the smaller the gradient of u_{dyn}/σ'_{vo} - n curves at the initial stage of cyclic shear. Especially, in the case of T=0.2s as shown in Fig.2, after the cyclic shear is stopped, a little increase in the excess pore water pressure is observed.

It has been shown in the previous study (Ref.4) that when normally consolidated kaolinite clay is subjected to cyclic shear strain under the undrained condition, excess pore water pressure increases with the number of cycles n, and that the relations between the excess pore water pressure and n were formulated by hyperbola, as follows,

$$u_{dyn}/\sigma'_{vo} = n \;/\; (\alpha + \beta \cdot n) \qquad (1)$$

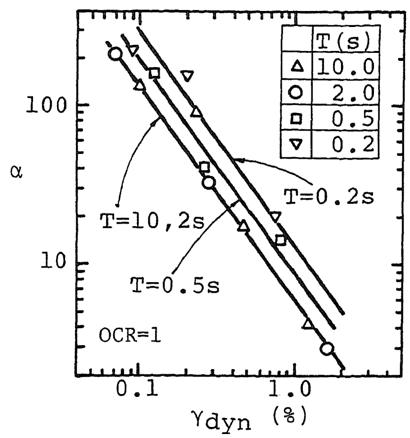

Fig.3 α versus Cyclic Shear Strain Amplitude.

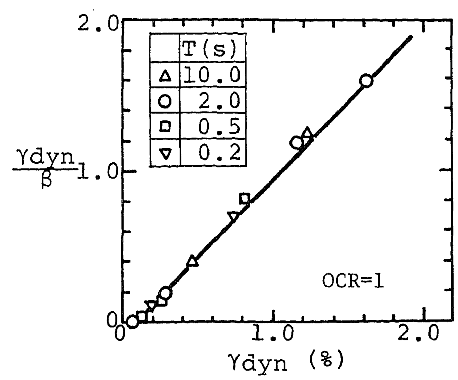

Fig.4 β versus Cyclic Shear Strain Amplitude.

where α and β are parameters. It is apparent that from Eq.(1), when n approaches infinity, u_{dyn}/σ'_{vo} becomes $1/\beta$.

In Figs.3 and 4, the relationships between α, β and the shear strain amplitude γ_{dyn} are shown for different periods of cyclic shear. From these figures, the following relations are derived.

$$\alpha = A \cdot (\gamma_{dyn})^m \qquad (2)$$

$$\beta = \gamma_{dyn} \;/\; (B + C \cdot \gamma_{dyn}) \qquad (3)$$

where A, B, C, and m are constants.

It is seen from Figs.3 and 4 that α decreases with increase of the periods and that β is independent of the periods. As mentioned above, this fact means that when n approaches infinity the excess pore water pressure converges to a certain constant value which depends on the shear strain amplitude.

For different shear strain amplitudes and periods, the relationships between u_{dyn}/σ'_{vo} and the number of cycles n calculated by Eqs.(1),(2) and (3) are shown in Fig.5. It is apparent from the same figure that when γ_{dyn} equals to 0.1%, the effects of the variation in the period on the excess pore water pressure can not be seen. When the shear strain amplitude increases, however, the larger the periods, the larger the initial gradient in u_{dyn}/σ'_{vo} vs. n curves becomes, and the excess pore water pressure calculated for respective periods are different at 200 cycles of shear.

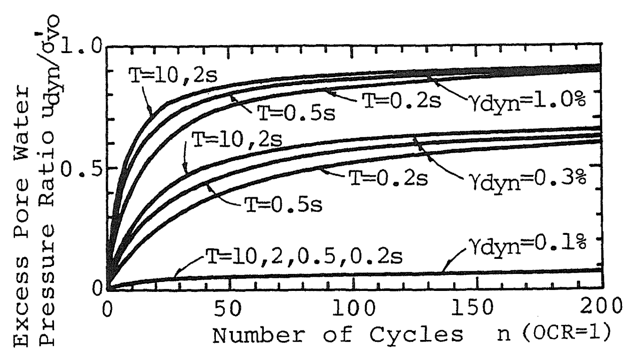

Fig.5 Excess Pore Water Pressure Calculated by Eq.(1).

From Eq.(1),

$$\Delta u_{dyn}/\sigma'_{vo} = \partial(u_{dyn}/\sigma'_{vo})/\partial n = \alpha/(\alpha + \beta \cdot n)^2 \tag{4}$$

where $\Delta u_{dyn}/\sigma'_{vo}$ is the increment of excess pore water pressure per strain cycle. The effects of period on the relationships between $\Delta u_{dyn}/\sigma'_{vo}$ and n are shown in Fig.6, for shear strain amplitude of 0.3%. It is seen from Fig.6 that for $n<30$, the larger the period, the larger the increment of excess pore water pressure becomes and that for $n>30$ the excess pore water pressure becomes larger with decrease of the period.

The effects of the period on the excess pore water pressure obtained by the tests as mentioned previously are shown in Fig.7; in the tests the number of cycles were restricted to 50 and from the start of the cyclic shear the excess pore water pressure was measured with time continuously for about 600s. From Fig.7, it can be seen that after the cyclic shear is stopped, the residual excess pore water pressures obtained for the periods of 10s and 2.0s are kept constant and that for the period of 0.5s, the residual excess pore water pressure increases and approaches the curves for the period of 10s and 2.0s. Such a results are also confirmed in the case of n=200 and Matsui (Ref. 5) has obtained the similar results by the stress-controlled cyclic triaxial tests.

EFFECTS OF PERIOD ON THE SETTLEMENT INDUCED BY AN EARTHQUAKE

When a clay layer is subjected to cyclic shear, the excess pore water pressure is produced. In case that the duration of cyclic

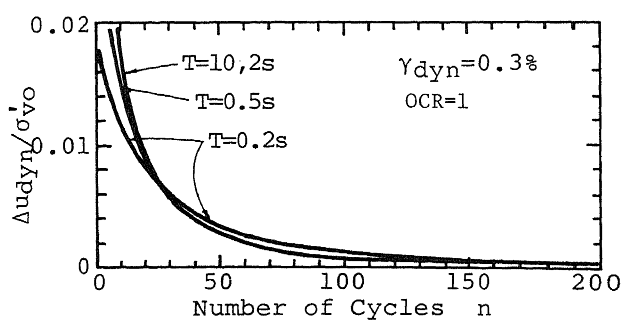

Fig.6 Relationships between $\Delta u_{dyn}/\sigma'_{vo}$ and n, for γ_{dyn}=1.0%.

loading is short as an earthquake, the dissipation of the excess pore water pressure lasts over a long time and then the ground subsidence occurs gradually after the earthquake. The relations between Δe and the logarithm of the increment of effective stress $\log(1/(1-u_{dyn}/\sigma'_{vo}))$ are shown in Fig.8 for different period of cyclic shear. Although the scattering is seen, Δe increases approximately in proportion to the logarithm of the increment of the effective stress, irrespective of the period. The gradient of the straight line in Fig.8 is called in this paper as "the dynamic compression index C_{dyn}". In Fig.8, the results for different shear strain amplitude are included and so, it is suggested that the dynamic compression index is independent of the period of cyclic shear.

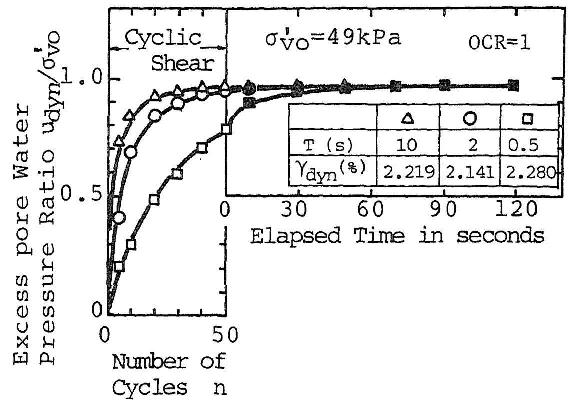

Fig.7 Relationships between u_{dyn}/σ'_{vo} and Elapsed Time.

The change of the void ratio Δe and the settlement in strain ε_v are able to be expressed as follows by using C_{dyn}.

$$\Delta e = -C_{dyn} \cdot \ell og\ (1/(1 - u_{dyn}/\sigma'_{vo})) \tag{5}$$

$$\varepsilon_v = -\Delta e/(1 + e_o) \tag{6}$$

or

$$\varepsilon_v = C_{dyn} \cdot \ell og\ (1/(1 - u_{dyn}/\sigma'_{vo}))\ /\ (1 + e_o) \tag{7}$$

where e_o is the initial void ratio.

The relationships between the settlement in strain and the shear strain amplitude are shown in Fig.9. Symbols in the figure correspond to the observed results and the solid curve to the calculated one by Eq.(7). It is seen that the solid lines are affected a little by the period of cyclic shear; the larger the period, the larger the settlement becomes. This is caused by the reason that u_{dyn} in Eq.(7) denote the excess pore water pressure which remains immediately after the cyclic shear is stopped. For the observed results, however, the effects of the periods can not be seen. So, it is considered that the settlement induced by the earthquake is not affected by the period of cyclic shear.

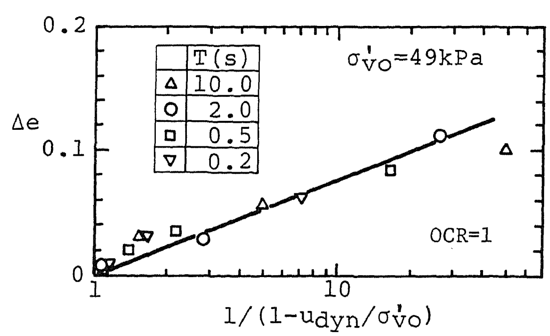

Fig.8 Change of the Void Ratio due to the Dissipation of the Excess Pore Water Pressure.

CONCLUSIONS

In this paper, normally consolidated clays were subjected to cyclic shear strain with different periods and followed by the dissipation of the excess pore water pressure induced by cyclic shear. Then the effects of periods on the excess pore water pressure generation and on the settlement were investigated. The important conclusions obtained in this study are as follows.

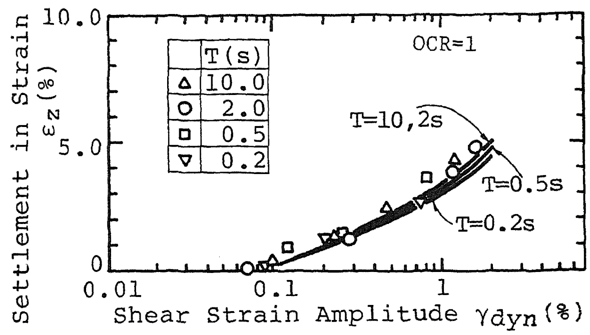

Fig.9 Settlement Induced by Cyclic Shear Strain.

1) The excess pore water pressure increases with increase of the periods of cyclic shear.

2) In the case that the period of cyclic shear is small as T=0.5s and 0.2s, the increase in the excess pore water is seen after the cyclic shear is stopped.

3) When the shear strain amplitude is constant, the residual excess pore water pressure induced by cyclic shear reaches a certain value irrespective of the period of cyclic shear.

4) The dynamic compression index C_{dyn} is not affected by the periods of cyclic shear.

5) The settlement induced by cyclic shear is independent of the periods of cyclic shear.

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