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SYNOPSIS This paper is mainly focussed on two parts: (a) to clarify the mechanism of migration of excess pore water pressure in clay specimen and (b) subsequent consolidation behavior after the dissipation of excess pore water pressure accumulated due to undrained cyclic loading. A new technique to measure the pore pressure at the mid-height periphery of a triaxial specimen was developed. The effect of loading frequency and the stress level on the generation of excess pore pressure at the top, bottom and at mid-height of the specimen has been discussed. The variation of recompression index due to the dissipation of excess pore pressure is investigated in detail and the results are compared with those obtained from undrained cyclic torsional simple shear tests.

INTRODUCTION

Clays when subjected to undrained cyclic loadings like earthquake loads, traffic loads etc., do not show drastic failure like liquefaction. However, many serious damages caused by the settlement of the clay layer due to the dissipation of induced excess pore water pressure has been reported (Zeevaert, 1972; Ohmachi et al. 1988 among others). Many researches, using either triaxial or direct simple shear tests, were reported on the behavior of clay subjected to undrained cyclic loading and subsequent drainage (Matsui et al., 1980; Ohara et al., 1988; Yasuhara et al., 1989; Yasuhara et al., 1991 among others). Yasuhara et al. (1989) has proposed some method to predict the recompression volumetric strain induced by the dissipation of accumulated excess pore pressure. They have used the value of recompression index obtained from Oedometer tests.

Concerning the researches on the behavior of clay subjected to cyclic loading, it seems that following two points have not been yet clarified: (a) the pore pressure distribution in the specimen during undrained loading and (b) the mechanism of clay behavior during the dissipation of excess pore pressure. It is because in most of the tests pore pressure are measured at the ends of the specimen. Some efforts have been made to measure the pore pressure at the mid-height center by inserting needle in the specimen. However, many difficulties and problems are encountered in such methods. Hight (1982) has also proposed a sophisticated method based on a miniature silicon diaphragm pressure transducer which is mounted with its porous ceramic face flush with the cylindrical surface of the specimen at mid-height. A technique to measure the pore pressure, by using a conventional pressure transducer, at the mid-height periphery of a triaxial specimen is proposed. This method does not disturb the specimen as no miniature transducer is inserted into the specimen.

In the present paper, a series of undrained cyclic triaxial tests were performed on reconstituted and pre-consolidated clay samples with different loading frequencies and loading intensities. The tests were terminated at some specified loading cycle and left for the equilibrium migration of the excess pore pressure throughout the specimen. Then the drainage from the top and the bottom end of the specimen were allowed and subjected to subsequent consolidation while measuring the pore pressure at the mid-height of the specimen. The consolidation mechanism has been investigated in detail by focussing on the variation of the recompression index.

Undrained cyclic torsional simple shear tests were also performed on anisotropically consolidated specimens and the data obtained from subsequent consolidation has been compared with those from triaxial tests.

SAMPLE AND TESTING METHOD

Clay obtained from Tokyo bay and after passing through 75μm sieve, was used. The physical properties were: liquid limit, 80%; plasticity index 45; specific gravity, 2.69. The samples were prepared by remolding the clay at twice of its liquid limit and preconsolidated one-dimensionally at a stress of 50 kPa.

Triaxial specimens 5cm in diameter and 10cm in height with regular ends were used. Drainage was allowed only from ends. Undrained cyclic loading tests were performed with three types of loading frequencies while measuring the pore pressure at the mid-height. All the specimens were isotropically consolidated to isotropic pressure of 100 kPa. On the other hand, undrained cyclic simple shear tests were performed on hollow cylindrical specimens (outer and inner diameter of 10cm and 6cm, height 5cm) with loading frequency of 0.1Hz only. Specimens were anisotropically consolidated to effective vertical stress (σ_{vc}') of 184 kPa and effective radial stress (σ_{rc}') of 100 kPa. Mid-height pore pressure was not measured in torsional simple shear tests. Back pressure of 200 kPa was applied to all specimens and Bishop's B- value of greater than 0.96 was obtained. A list of testing conditions for triaxial tests are shown in Table 1.

Table 1 Testing conditions and results

Test No.	e_0	e_c	$q/2\sigma_c'$	f(Hz)	N_c	$\Delta u/\sigma_c'$	DA_{max}(%)	Δe
TC-1	1.752	1.495	0.20	0.2	500	0.345	0.7	0.016
TC-2	1.783	1.511	0.22	0.2	500	0.612	1.4	0.037
TC-3	1.782	1.496	0.25	0.2	213	0.843	5.6	0.091
TC-4	1.737	1.497	0.20	0.1	500	0.400	0.7	0.019
TC-5	1.768	1.494	0.23	0.1	500	0.637	1.4	0.042
TC-6	1.792	1.495	0.25	0.1	145	0.743	3.1	0.064
TC-7	1.777	1.494	0.20	0.05	500	0.501	1.0	0.027
TC-8	1.784	1.492	0.23	0.05	240	0.875	7.6	0.117
TC-9	1.776	1.499	0.25	0.05	110	0.905	11.6	0.134

※ DA_{max}(%): Double amplitude axial strain
Δe : Void ratio change due to dissipation

MEASUREMENT OF PORE PRESSURE AT MID-HEIGHT OF SPECIMEN

A synflex tube is flattened at its one end by heat and attached to the membrane by a super bond (Permabond 268) as shown in Fig.1. That membrane is then used to wrap the specimen and the other end of the tube is connected to a conventional pressure transducer placed outside the cell. Flushing could be done easily by applying a small vacuum and percolation of deaired water through bottom of the specimen to middle synflex tube connected to the transducer.

Typical results for a clean sand and a clay are depicted in Figs 2 and 3, when subjected to undrained cyclic loading of frequency 0.1 Hz. It can be observed that for sand, the pore pressure responses at the top, bottom and mid-height are identical and no time lag was noticed (Fig.2). This data corroborates the reliability of the proposed method. However, in case of clay specimen (Fig.3), the pore pressure response at mid-height is different from those at top and bottom even at a loading frequency of 0.1 Hz. This difference in response is due to the low permeability of the clay specimen and the features will be discussed later. The pore pressure responses at top and bottom are reasonably identical and hence the average value of top and bottom were measured.

PORE PRESSURE RESPONSE DURING CYCLIC LOADING

Typical pore pressure responses for clay subjected to different loading frequencies are shown in Figs 4 and 5. Following points could be noticed: (a) the induced pore pressure is smaller when loading frequency is higher, (b) the time lag (Δt) and the difference in amplitude of the pore pressures at the mid-height (u_m) and at top and bottom (u_a) is larger at higher frequency. The dependency of generated pore pressure measured at ends on the loading frequency has also been reported by many researcher (Matsui et al., 1980, among others). However, it should be emphasized here that the non-uniform pore pressure distribution along the specimen height becomes predominant at higher loading frequency. The ratio of the time lag Δt to the loading period (T) and the amplitude ratio u_m/u_a is shown in Table 2. It can be observed that the amplitude ratio becomes larger for smaller frequency implying that the pore pressure response will be uniform for very small loading rate. The time lag seems to decrease with smaller frequency.

Fig.6 shows the effect of frequency on induced peak pore pressures for the same stress level. It can be noticed that the peak pore pressure at the top and bottom is always greater than that at the mid-height irrespective of frequency and stress level until a certain value of pore pressure ratio. At higher pore pressure ratio associating a larger strain, the peak at mid-height becomes larger than that at top and bottom. However, it can be noticed from Figs 4 and 5 that the average value in each cycle of the pore pressure at mid-height is greater than that at top and bottom. The above mentioned facts are indicating that the migration of pore pressure is occurring during cyclic loading which depend on the loading frequency, stress intensity and the permeability of the soil.

Table 2 Comparison of pore pressure responses

Test No.	$q/2\sigma_c'$	f(Hz)	$\Delta t/T$(%)	um/ua
TC-2	0.22	0.2	15.0	0.286
TC-5	0.23	0.1	10.8	0.379
TC-8	0.23	0.05	9.0	0.474

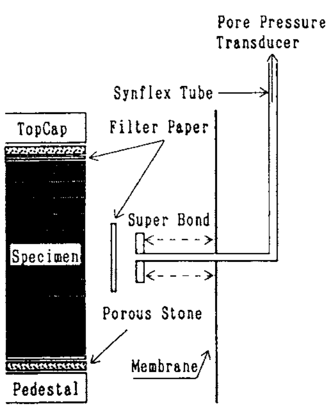

Fig.1 Setting for mid-height pore pressure measurement

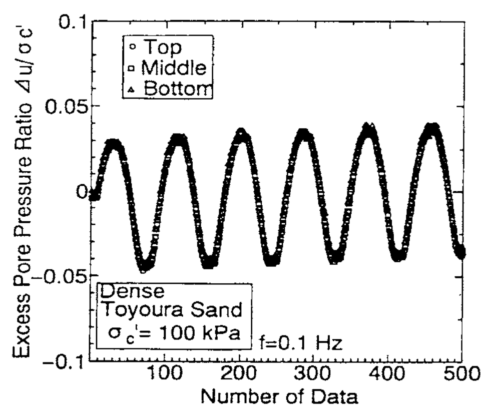

Fig.2 Typical result for clean sand

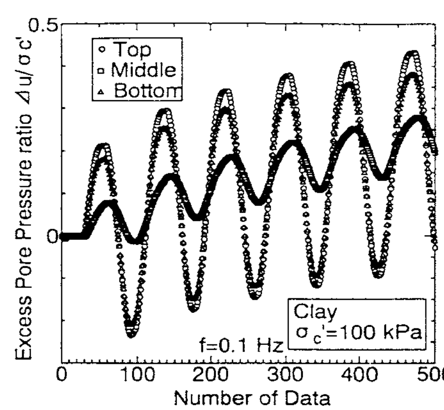

Fig.3 Typical result for clay

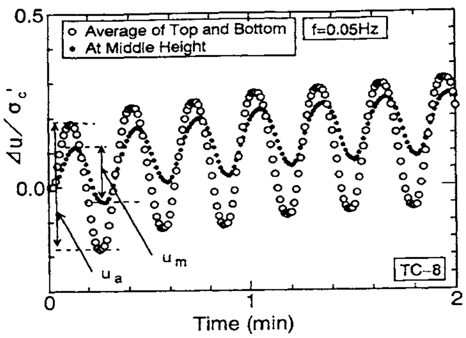

Fig.4 Pore pressure response at f=0.05 Hz

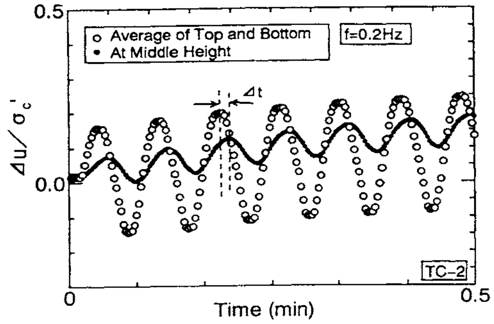

Fig.5 Pore pressure response at f=0.20 Hz

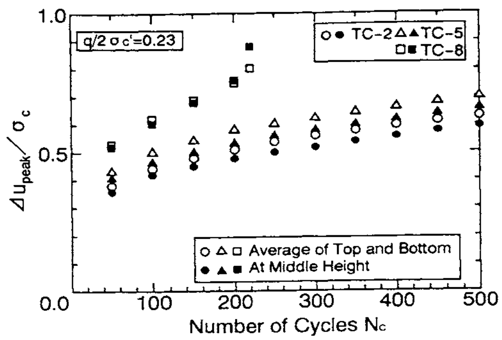

Fig.6 Peak pore pressure versus loading cycles

RESIDUAL PORE PRESSURE AFTER CYCLIC LOADING

When the cyclic loading is terminated at a specified number of cycles, the residual pore pressure at the mid-height is always greater than that at top and bottom. The magnitude of this difference depend on the degree of accumulated excess pore pressure and also on the loading frequency. The residual pore pressure is almost equal to the average pore pressure at the last cycle. The residual pore pressures for two tests where the accumulated pore pressures are relatively different corresponds to the time zero in Fig.7. It can be noticed that the residual pore pressure is almost uniform when the excess pore pressure ratio ($\Delta u/\sigma_c'$) is about 50% (TC-7). However, if this ratio is large the non-uniformity of the pore pressure is significant with higher pore pressure at the mid-height (TC-3). The residual pore pressure at the mid-height is about 30% higher than that measured at top and bottom. Hence the migration of pore pressure will occur and equilibrium uniform pressure will be attained after some time. It is clear from Fig.7 that the time required for the equilibrium of pore pressure depends on the degree of accumulated pore pressure. For test TC-7, 20 minutes is enough for equilibrium while for test TC-3, about 3 hours is necessary for fully equilibrium condition to be attained. This equilibrium residual pore pressure for all the tests are shown in Table 1.

SUBSEQUENT CONSOLIDATION BEHAVIOR

After the equilibrium of pore pressure inside the specimen has attained, drainage was allowed from both ends of the specimen while measuring the pore pressure at the mid-height. The recovery of the effective stress occurs instantly at the ends and gradually at the mid-height and its vicinity.

Typical recorded data for whole process from isotropic consolidation to subsequent consolidation is depicted in Fig.8. Path BC is undrained cyclic loading and C represents the effective stress at the equilibrium state. Path CD is the subsequent consolidation path plotted by using the pore pressure measured at the mid-height. This path cannot be depicted if the pore pressure is measured at drainage ends. D is the point where full recovery of effective stress in the specimen is attained and the change in void ratio Δe is calculated from settlement upto the end of primary consolidation. The overall recompression index C_r' can be expressed by eqn. (1).

$$C_r' = \Delta e/\{\log(p_D'/p_C')\} = \Delta e/\{\log(1/(1-\Delta u/\sigma_c'))\} \quad ---(1)$$

Here, Δu is the accumulated excess pore pressure at the equilibrium stage and $\sigma_c'(=p_p')$ is the isotropic effective consolidation pressure. In order to know the variation of recompression index during the dissipation of pore pressure at any arbitrary effective pressure p_E', C_r^* is defined as eqn. (2) and graphically illustrated in inset of Fig.8.

$$C_r^* = de/d(\log p_E') \quad --- (2)$$

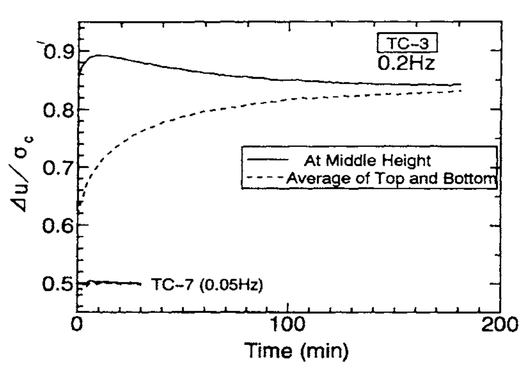

Fig.7 Migration of pore pressure after cyclic loading

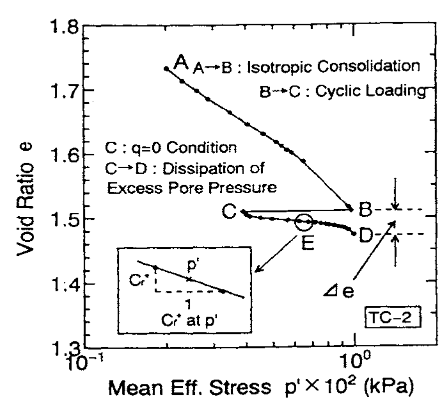

Fig.8 e - p' curve showing whole process

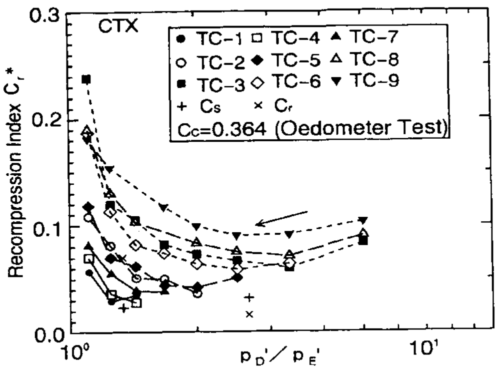

Fig.9 Variation of recompression index

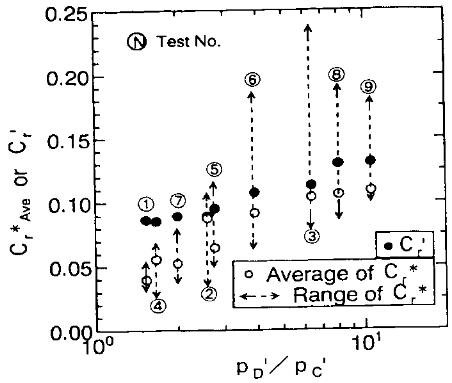

Fig.10 Variation of different recompression indices

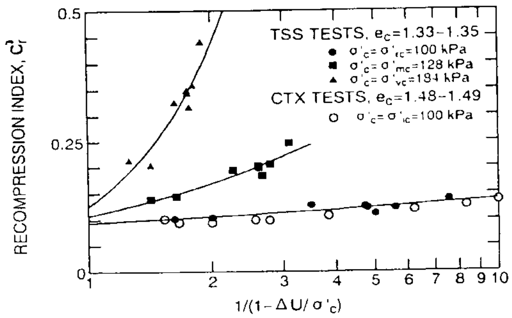

Fig.11 Comparison of recompression indices

The variation of C_r^* with pressure level is shown in Fig.9 for all the tests. It can be noticed that C_r^* decreases at the initial stage and increases rapidly at the final stage of the consolidation. In the same figure, swelling index (C_s) and recompression index (C_r) from Oedometer test with two steps of unloading and reloading paths are shown. The unloading was carried out at 160 kPa in order to make the same mean stress level with that in triaxial tests. C_r increases near the normally consolidation region and the tendency is similar to that of C_r^*. The average value for C_r was 0.045. The range of C_r^* and its non-linear average $C_{r\,ave}^*$ and C_r' are shown in Fig.10. Following points can be noticed: (a) C_r' is not constant and increases slightly with the degree of accumulated excess pore pressure, (b) $C_{r\,ave}^*$ is smaller than Cr', (c) average value of C_r' is about 2.3 times of average value of C_r from Oedometer test unloaded at the equivalent stress level. Yasuhara et al. (1991), had shown from the data of anisotropically consolidated cyclic direct simple shear tests that recompression index may be calculated as 1.5 times of that from Oedometer test.

The comparison of recompression indices from isotropically consolidated triaxial tests (CTX) and anisotropically consolidated torsional simple shear cyclic tests (TSS), are shown in Fig.11. In case of anisotropically consolidated specimen, C_r' can be calculated in three different methods by using eqn. (1) as: (a) $\sigma_c'=\sigma_r'$ (effective radial consolidated stress), (b) $\sigma_c'=\sigma_v'$ (effective vertical consolidated stress) and (c) $\sigma_c'=\sigma_m'$ (effective mean consolidated stress). The values are shown in Fig.11. It is interesting to note that C_r' calculated from method (a) is identical to those from triaxial tests irrespective of the loading frequency, stress level and testing methods. The largest values of C_r' were obtained when calculated by method (b). One of the reason may be that the degree of induced excess pore pressure (Δu) in TSS tests is controlled by σ_r' since Δu can never exceed σ_r'. Hence it seems reasonable to calculate C_r' by using the excess pore pressure expressed in terms of $\Delta u/\sigma_r'$. It should also be stated that C_r' calculated by using σ_v' is of the same order as compression index (C_c =0.364) from Oedometer test.

CONCLUSIONS

Following conclusions could be drawn from the limited number of tests performed in this study.

(a) A simple technique of measuring pore pressure at the mid-height periphery of the specimen is proposed.

(b) The pore pressure distribution inside the specimen depends on the level of stress ratio applied and the loading frequency.

(c) The residual pore pressure (Δu) at the mid-height is greater than that at bottom and the time required to attain equilibrium state depends on the degree of Δu.

(d) The recompression index decreases slightly at the beginning of the subsequent consolidation and increases at the last part.

(e) Recompression index (C_r') from cyclic triaxial and torsional simple shear tests are almost identical if C_r' is calculated using effective radial consolidation stress.

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