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TWO MODELS FOR THE ESTIMATION OF CYCLIC SHEAR-INDUCED PORE WATER PRESSURE AND SETTLEMENT ON NORMALLY CONSOLIDATED CLAYS

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ABSTRACT

Normally consolidated clay specimens with different Atterberg's limits were subjected to undrained uni-directional and multi-directional cyclic shears which were followed by the drainage. Then the pore water pressure and the post-cyclic settlement were measured with time and based on which, effects of the cyclic shear conditions on such properties were clarified and also estimation methods for the cyclic shear-induced pore water pressure accumulation and settlement were developed by incorporating the plasticity index as a function of experimental constants. The applicabilities of developed estimation methods were then confirmed.

Keywords: Atterberg's limits, clay, pore water pressure, settlement, undrained cyclic shear.

1. INTRODUCTION

When a clay layer is subjected to the earthquake-induced cyclic shear, pore water pressure may accumulate to a relatively high level which results in an additional settlement of clay layers [1,2]. Although the post-earthquake settlements of cohesive soils have been observed under various kinds of cyclic loading conditions, effect of the cyclic shear direction has been preliminarily observed [1,3]. In addition, based on the undrained cyclic simple shear test results, Nhan *et al.* [1] clarified the effects of the soil plasticity on the pore water pressure accumulation and the consolidation characteristics of cohesive soils. Since Atterberg's limits are usually obtained as a fundamental physical property in geotechnical engineering, the plasticity index was especially used as a specific parameter when evaluating the dynamic properties of soil deposits.

2. EXPERIMENTAL ASPECTS AND CALCULATION METHODS

2.1. Experimental aspects

In this study, three kinds of clays were used. Physical properties of these clays are shown in Table 1. Cyclic shear tests were carried out by using by the multi-directional cyclic simple shear test apparatus which was developed at Yamaguchi University (Japan). Reconstituted specimen of each clay was firstly pre-consolidated under the vertical stress σvo = 49 kPa and was then subjected to undrained cyclic shear for number of cycles (n = 200), shear strain amplitude (γ = 0.05% ÷ 3.0%) and cyclic shear directions (uni-direction and multi-direction with various phase differences). Following the undrained cyclic shear, drainage was allowed and the pore water pressure and the settlement were measured with time.

Table 1. Physical properties of used clays

Property	Kitakyushu clay	Tokyo bay clay	Kaolin
Specific gravity, G_s	2.63	2.77	2.71
Liquid limit, w_L (%)	98.0	66.6	47.8
Plastic limit, w_P (%)	34.2	25.0	22.3
Plasticity index, I_p	63.8	41.6	25.5
Compression index, C_c	0.60	0.46	0.31

2.2. Calculation methods of cyclic shear-induced pore water pressure and settlement

Ohara *et al.* [4] proposed an equation showing the relations between the pore water pressure ratio which is defined by U_{dyn}/σ'_{vo}, and the number of cycles n as follows:

$$\frac{U_{dyn}}{\sigma'_{vo}} = \frac{n}{\alpha + \beta n} \tag{1}$$

This equation was then developed by Matsuda *et al.* [5] by using a new parameter as Eq. (2).

$$\frac{U_{dyn}}{\sigma'_{vo}} = \frac{G^*}{\alpha + \beta G^*} \tag{2}$$

where σ'_{vo} is the initial effective stress, U_{dyn} is the cyclic shear-induced pore water pressure, G^* is the cumulative shear strain which is a function of γ and n as Eqs. (3) and (4). [5]

For uni-direction: $G^* = n\,(3.950\,\gamma + 0.0523)$ (3)

For multi-direction: $G^* = n\,(5.995\,\gamma + 0.3510)$ (4)

α and β are the experimental parameters and a function of γ, as follows:

$$\alpha = A(\gamma)^m \tag{5}$$

$$\beta = \frac{\gamma}{B + C\gamma} \tag{6}$$

A, *B*, *C* and *m* are experimental constants. Eqs. (1) and (2) were applied for estimating the cyclic shear-induced pore water pressure and based on which, the post-cyclic settlement can be predicted by using Eq. (7).

$$\varepsilon_v = \frac{\Delta h}{h_o} = \frac{\Delta e}{1+e_o} = \frac{C_{dyn}}{1+e_o}\log\left(\frac{1}{1-\dfrac{U_{dyn}}{\sigma'_{vo}}}\right) = \frac{C_{dyn}}{1+e_o}\log SRR \tag{7}$$

where ε_v is the settlement in strain, h_o and e_o are the initial height and initial void ratio of soil specimen, Δh and Δe are the change in specimen height and the void ratio, C_{dyn} is the cyclic recompression index and $SRR = 1/(1-U_{dyn}/\sigma'_{vo})$ is called as the stress reduction ratio.

3. RESULTS AND DISCUSSION

3.1. Estimation of the pore water pressure accumulation

By using the curve-fitting method, experimental constants were determined in relation with the plasticity index I_p as shown in Table 2. Comparisons between observed and calculated results for the relations of U_{dyn}/σ'_{vo} versus γ and G^* are shown in Figs. 1(a) and 1(b), respectively. Symbols in these figures show the experimental results, and solid and dashed lines show ones calculated by using Eqs. (1) and (2), where the experimental constants were determined by using the relations in Table 2. The calculated results agree well with the observed ones and therefore, Eqs. (1) and (2) are valid for estimating the cyclic shear-induced pore water pressure of clays with a wide range of Atterberg's limits.

Table 2. Experimental constants A, B, C and m in relation to I_p by using Eqs. (1) and (2)

Experimental constants	By using Eq. (1)		By using Eq. (2)	
	Uni-direction	Multi-direction	Uni-direction	Multi-direction
A	$A = 7.5606\,I_p - 188.150$	$A = 3.9518\,I_p - 97.798$	$A = 25.268\,I_p - 608.87$	$A = 19.240\,I_p - 479.83$
B	$B = -0.0042\,I_p + 0.0229$	$B = -0.0004\,I_p - 0.0417$	$B = -0.0017\,I_p - 0.0321$	$B = -0.0003\,I_p - 0.0537$
C	$C = -0.0047\,I_p + 1.1569$	$C = -0.0037\,I_p + 1.1190$	$C = -0.0074\,I_p + 1.1993$	$C = -0.0071\,I_p + 1.2042$
m	$m = 0.0226\,I_p - 2.9534$	$m = 0.0200\,I_p - 2.5904$	$m = 0.0236\,I_p - 1.9318$	$m = 0.0228\,I_p - 1.8761$

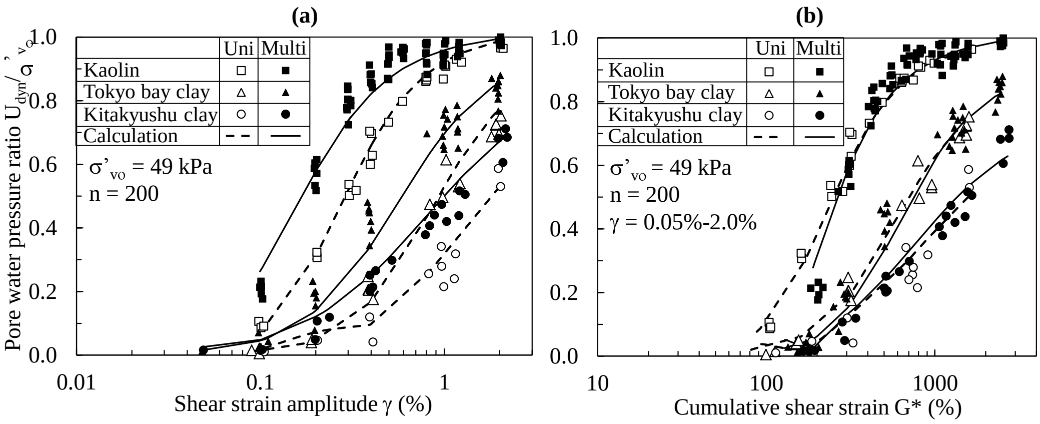

Figure 1. Relationships of U_{dyn}/σ'_{vo} versus γ and G^* for clayey soils with a wide range of Atterberg's limits subjected to undrained uni-directional and multi-directional cyclic shears

3.2. Prediction of the post-cyclic settlement

As for the post-cyclic settlement, observed results of relationships between Δe and SRR are shown by symbols in Fig. 2, and solid and dashed lines correspond to the calculated ones by using Eq. (7) in which $SRR_{(\gamma)}$ and $SRR_{(G^*)}$ were determined by using the calculated results as shown in Figs. 1(a) and 1(b), respectively. In spite of scatterings on the observed results, relatively reasonable agreements are seen. Then the cyclic recompression indices were obtained and shown as a function of I_p in Table 3.

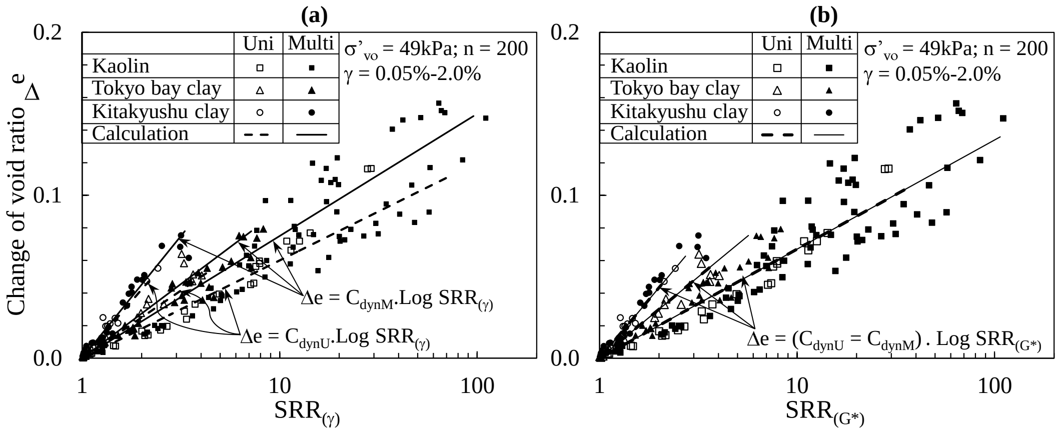

Figure 2. Change of the void ratio of clays with a wide range of Atterberg's limits under undrained uni-directional and multi-directional cyclic shears.

Table 3. Relation between the cyclic recompression index with the plasticity index

By using $SRR_{(\gamma)}$		By using $SRR_{(G^*)}$
$C_{dynU} = 0.0021\ I_p + 0.0019$	$C_{dynM} = 0.0020\ I_p + 0.0180$	$C_{dynU} = C_{dynM} = 0.0020\ I_p + 0.0160$

Vertical settlements in strain ε_v are plotted by symbols against γ and G^* in Figs. 3(a) and 3(b), respectively. Dashed and solid lines show the calculated ones by using Eq. (7), in which C_{dynU} and C_{dynM} were obtained by using relations in Table 3. Calculated results reasonably agree well with the observed ones. Therefore, the prediction of the post-cyclic settlement by using such developed methods as shown above is confirmed. In Figs. 1(a) and 3(a), the discrepancies in U_{dyn}/σ'_{vo} and ε_v between uni-direction and multi-direction are evident which indicates the effects of the cyclic shear direction are not negligible when using γ. Meanwhile by using G^* as shown in Figs. 1(b) and 3(b), these differences disappear, which means the elimination of such factors as the cyclic shear direction.

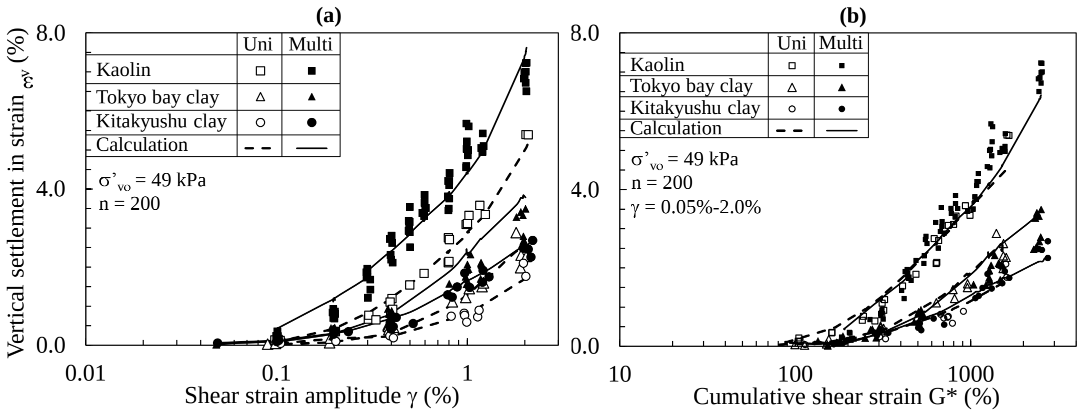

Figure 3. Relations of ε_v versus γ and G on clays with a wide range of Atterberg's limits subjected to uni-directional and multi-directional cyclic shears*

4. CONCLUSIONS

Several series of undrained cyclic shear tests were carried out on clays with different Atterberg's limits and the effects of cyclic shear direction on the cyclic shear-induced pore water pressure accumulation and settlement were observed. These effects of the cyclic shear direction can be eliminated by using G^* meanwhile effects of Atterberg's limits on these properties still remain. So, by incorporating Atterberg's limits into a function of the experimental constants, the cyclic shear-induced pore water pressure and settlement can be estimated for clayey soils with a wide range of Atterberg's limits.

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REFERENCES

[1]. Trần Thanh Nhàn, Hiroshi Matsuda, Hidemasa Sato, 2017. A model for multi-directional cyclic shear-induced pore water pressure and settlement on clays. Bulletin of Earthquake Engineering, 15(7), 2761-2784.

[2]. Kazuya Yasuhara, Knut H. Andersen, 1991. Recompression of normally consolidated clay after cyclic loading. Soils and Foundations, 31(1), 83-94.

[3]. Trần Thanh Nhàn, Hiroshi Matsuda, Hiroyuki Hara, Hidemasa Sato, 2015. Normalized pore water pressure ratio and post-cyclic settlement of saturated clay subjected to undrained uni-directional and multi-directional cyclic shears. 10th Asian Regional Conference of IAEG, Paper No. Tp3-16-1081481, 1-6.

[4]. Sukeo Ohara, Hiroshi Matsuda, Yasuo Kondo, 1984. Cyclic simple shear tests on saturated clay with drainage. Journal of JSCE Division C, 352(III-2), 149-158.

[5]. Hiroshi Matsuda, Trần Thanh Nhàn, Ryohei Ishikura, 2013. Prediction of excess pore water pressure and post-cyclic settlement on soft clay induced by uni-directional and multi-directional cyclic shears as a function of strain path parameters. Journal of Soil Dynamics and Earthquake Engineering, 49, 75-88.