CONSOLIDATION OF ALLUVIAL CLAY UNDER REPEATED LOADING

HARUO FUJIWARA*, TOYOTOSHI YAMANOUCHI**,
KAZUYA YASUHARA*** and SHUNJI UE****

ABSTRACT

When repeated loads are applied to a foundation, the deformation of the foundation soil may increase significantly in comparison with the case of static load applications. For this reason an unconventional calculation in the case of repeated loading needs to be made for estimating the deformation of the soil. Among the various types of repeated loads some typical examples are earthquake forces, vehicle loads and oil storage tank loads.

Specially-devised consolidation tests under static and repeated loading were performed on remolded saturated cohesive soil samples. The samples under repeated loading conditions were more compressible than those under static loading conditions, and the difference in compressibility or settlement between these two loading conditions seems to be due to secondary compression and the change in soil particle structures.

As the settlement of the foundation under repeated loading is caused and governed primarily by the magnitude of total load, the loading period, the load increment ratio and the number of load cycles, it is suggested that all of these factors should be considered in predicting the settlement induced by repeated loading. In this paper, therefore, we aim at presenting some basic data and an interpretation of the consolidation of clay under repeated loading. In addition, based on a simplified method for prediction, a case study of settlement calculation is shown for an oil tank foundation on clay. The necessity of repeated oedometer tests and their analysis is emphasized by comparison of settlement under cyclic loading with that under static loading.

Key words : cohesive soil, consolidation, repeated load, secondary compression, settlement, soil structure (IGC : D 5/D 7/E 8)

* Associate Professor, Department of Civil and Architectural Engineering, Tokuyama Technical College, Kume 3538, Tokuyama 745.

** Professor, Department of Civil Engineering, Kyushu Sangyo University, Higashi-ku, Fukuoka 813.

*** Professor, Department of Civil Engineering, Nishinippon Institute of Technology, Kanda 1633, Fukuoka 800-03.

**** Lecturer, Department of Civil and Architectural Engineering, Tokuyama Technical College, Kume 3538, Tokuyama 745.

Manuscript was received for review on June 3, 1983.

Written discussions on this paper should be submitted before April 1, 1986, to the Japanese Society of Soil Mechanics and Foundation Engineering, Sugayama Bldg. 4 F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101, Japan. Upon request the closing date may be extended one month.

INTRODUCTION

Basic data on the consolidation of clay under repeated loading are not perfect and some problems, such as secondary compression, have been left unsolved until now. Our study aims at obtaining some fundamental data regarding the consolidation under repeated loading, a subject which has not received sufficient attention even in the field of soil dynamics.

Many geotechnical engineers have pointed out that the influence of repeated loading on soft ground should be carefully investigated. Typical problems encountered with this type of clay include those induced by earthquake forces, vehicle loads, wind or wave actions on off-shore structures and statically repeated oil storage tank loads.

Various other studies of soil deformation induced by the application of repeated loading have been carried out. The majority of this kind of research during the 1950's was conducted on various materials in connection with design problems related to pavement subgrades. Seed and his associates have made significant contributions to the early research in this field (for instance, Seed et al., 1955; Seed and Chan, 1958). Studies similar to that by Seed et al. were carried out by Kawakami and Ogawa (1965), and by Yamanouchi and Luo (1973). A number of works on the cyclic loading of saturated clay have recently emerged regarding the construction of off-shore structures on clay (Andersen et al., 1976). Most of the studies on cyclic loading of clay are limited to undrained shear behaviour, which is one of the factors related to the stability of foundations on clay, but there have been few studies on the consolidation or drained creep of clay under cyclic loading (Brown et al., 1977). Although these factors seem to have been of practical importance in the long-term settlement of off-shore structures, oil storage facilities, and so on (Bjerrum, 1966), we have not yet established a method for predicting this kind of settlement induced by cyclic or transient loading.

Fig. 1. The apparatus used in testing consolidation and relationship between consolidation pressure and time

Research by Yamanouchi et al. (1971) was the first to deal with the consolidation of alluvial clay under cyclic loading. Yasuhara et al. (1983) further investigated this problem through repeated triaxial compression tests under drained conditions. However, there are still some unsolved problems related to consolidation under cyclic loading. Therefore, in the present research consolidation tests under static and repeated loading on remolded saturated cohesive soil have been carried out for the purpose of studying the influence of variables—such as the total load, the loading period, the load increment ratio and the number of load cycles—on the characteristics of unrecoverable deformation of alluvial clay under cyclic loading.

TEST APPARATUS AND TEST PROCEDURE

The apparatus used in the consolidation tests under static and repeated loading is shown in Figs. 1(a) and 1(b); this apparatus is a modification of the conventionally used standard oedometer, adapted for use with static and repeated loading applied either separately or simultaneously. The consolidation pressures for typical repeated consolidation tests are illustrated in Fig. 1(c).

The soil used in this experiment was obtained from beneath the foundations of existing oil storage tanks in Kudamatsu city. Its index properties are shown in Table 1.

Table 1. Index properties of soils used

Index properties	Kudamatsu clay	Ariake clay
Specific gravity of particle G_s	2.648	2.650
Liquid limit W_L (%)	65	115
Plastic limit W_P	30	57
Plasticity index I_P	35	58

The Kudamatsu clay was remolded at a moisture content of about 65%, which is almost equal to the liquid limit and was isotropically consolidated in a large-triaxial consolidated chamber under the confining pressure of 60 kPa for two weeks; the soil sample prepared by this method was then cut into a size (2 cm in height and 6 cm in diame-

ter) suitable for our oedometer tests.

An oil storage tank (22 m in height and 44 m in diameter) was constructed on a soft clayey layer of 30 m thickness underlain by a sandy drainage layer. The static pressure p consists of an overburden pressure and a vertical pressure due to a tank and sandbed, measured at various depths below the center of the tank; the portion of the vertical pressure Δp which is due to oil weight is given by the following common formula:

$$\Delta p = q \left\{ 1 - \left(\frac{1}{1 + (R/Z)^2} \right) \right\}^{3/2} \quad (1)$$

where Δp is the vertical pressure, q is the equivalent uniform pressure due to oil weight applied at the surface, R is the diameter of tank and Z is the depth.

The profile of the foundation of the oil storage tank and the vertical pressure under the center of the tank is shown in Fig. 2.

Fig. 2. Profile of the foundation of oil storage tank and vertical stress under the center of tank

Simulating typical actual oil storage conditions, for these experiments the whole process of filling the tank with oil and then draining away the oil supply was completed in about one month, and the degree of consolidation at any given depth during this one-month cycle was found to be proportional to the depth; this process was repeated for a long period of time. For these conditions we can determine the loading period at any depth according to the following formula:

$$T_v = \frac{t_1 c_v}{Z^2} \quad (2)$$

where T_v is the time factor, t_1 is the time (one month) and c_v is the coefficient of consolidation. We substitute T_v of Eq. (2) into T_v of Eq. (3).

$$t_2 = \frac{T_v D^2}{c_v} = \frac{t_1 D^2}{Z^2} \quad (3)$$

where t_2 is the loading period and D is the length of the drainage path of the sample.

Although the above mentioned method may not be totally adequate, and although the above formula which is effective for static consolidation is not always effective for repeated consolidation, we have adopted this method in order to obtain a rough estimation of a loading period.

After the actual subsoil is consolidated under overburden pressure, it is further consolidated under the pressure of repeated loading of oil weight over a long period of time. In order to determine a means of predicting the subsequent settlement, we performed the following consolidation tests: In the first step, the sample was consolidated under a static pressure p for 48 hours; in the second step, the sample was consolidated under both a static pressure p and a repeated pressure Δp simultaneously for 96 hours; and in the final step it was consolidated under the static pressure $p + \Delta p$ for 48 hours in order for us to observe the subsequent settlement. The loading sequences are shown in Table 2.

Table 2. Experimental conditions (case-1) (Kudamatsu clay)

No.	Z (m)	p (kPa)	Δp (kPa)	$\Delta p/p$	$p + \Delta p$ (kPa)	period (sec)
1	1	49	216	4.4	265	2072
2	3	88	216	2.4	304	230
3	5	118	216	1.8	333	83
4	7	147	206	1.4	353	42
5	10	196	196	1.0	392	21
6	15	274	176	0.6	451	9
7	20	353	147	0.4	500	5
8	30	519	98	0.2	617	2

In order to investigate the effect of cycle period on the settlement, the consolidation tests were carried out under the condition of a constant loading cycle period (83 sec), and we compared these results with the results

which were obtained under the condition where the loading period was changed in proportion to the depth.

For investigating the effect of the load increment ratio (hereafter referred to as LIR in this paper) $\Delta p/p$ additional consolidation tests were carried out under the condition that the total pressure $p + \Delta p$ was maintained at a constant level but the LIR $\Delta p/p$ was changed. For this series of experiment, the static consolidation tests were performed at the same time as the repeated consolidation tests, and the same loading conditions were used in both types of tests. After the completion of these tests, we examined all of the samples using the standard consolidation test in order to

Fig. 3. Time-settlement curves at the second and final step under static and repeated loading (Kudamatsu clay)

study the influence of the repeated loading history on the initial soil particle structure and on the consolidation characteristics.

TEST RESULTS AND DISCUSSION

The time versus settlement curves obtained by repeated oedometer tests on the Kudamatsu clay are shown in Fig. 3. At the depths of 1 m and 3 m, after subjecting the sample to 100% primary consolidation under static loading, the amount of settlement of the sample after repeated loading is larger than the settlement after static loading. At the depths of 7 m and 10 m, after a certain time the settlement of the sample under repeated loading is a little larger than that of the sample under static loading, while at the depths of 15 m and 20 m after a certain time the amounts of settlement of both samples are approximately equal. The same difference between static consolidation and re-

peated loading consolidation can be seen in Figs. 4(a) and 4(b) in the results of tests on Ariake clay. From the vertical strain versus time curves in Figs. 4(a) and 4(b), it can be seen that after a certain time the vertical strain of the sample under repeated loading seems to be greater than that under static loading. A comparison was made between the coefficient of volume compressibility m_v (which we calculated after 24 hours of settlement) and the coefficient of secondary compression ϵ_a for both types of consolidation test on Ariake clay, and the results are illustrated in Figs. 5(a) and 5(b). We can ascertain from these two figures that the repeated loading with the condition of non-lat-

Fig. 4. Comparison of axial strain-time relationship at the second step between repeated and static consolidation tests on Ariake clay (Yamanouchi et al.)

Fig. 5. Influence of repeated loads on coefficient of volume compressibility and secondary compression rate on Ariake clay (Yamanouchi et al.)

eral strain accelerates the consolidation of clay samples more significantly than the static loading particularly in the case of the secondary compression rather than primary consolidation.

In consequence, for the oil storage tank the magnitude of the final settlement after repeated loading depends upon the depth beneath the tank, and the difference in the final settlement between static and repeated consolidation is found to be larger in shallow layers than in deep layers. In other words, the larger LIR and larger loading period of repeated loading makes the clay layer consolidate to a greater extent. And it seems

Fig. 6 (a). Relationship between coefficient of consolidation c_v and depth z

Fig. 6 (b). Relationship between coefficient of volume compressibility m_v and depth z

that the settlement under repeated loading tends to continue for a long period, and the sample under repeated loading shows a large amount of secondary compression. In actual conditions, because of the above reasons and also because of the non-homogeneity of the foundation soil, there is a great possibility of differential settlement. This matter will be referred to in the latter part of the paper.

The coefficient of consolidation c_v and the coefficient of volume compressibility m_v obtained from the results of the standard consolidation tests after the repeated consolidation tests are shown in Figs. 6(a) and 6(b), respectively. At layers deeper than -10 m from the surface the values of c_v of the samples subjected to repeated loading are not different from those subjected to static loading, and the varying tendency of the values of m_v is similar to that of the values of c_v . At layers shallower than -10 m, however, the values of c_v of the samples subjected to repeated loading are different from those subjected to static loading; but at this depth also, the varying tendency of the values of m_v is similar to that of the values of c_v . Hence it is clear that there is some difference in the amount of settlement between static and repeated consolidations in the shallow layers.

Since both the coefficient of consolidation c_v and the coefficient of volume compressibility m_v of the shallow layer are different from those of the deep layer, as described before, we defined the boundary depth between the shallow layer and the deep layer as -10 m from the surface depth. And for the purpose of comparing the intervals of loading periods,

Table 3. Experimental conditions (case-1) (Kudamatsu clay)

No.	p (kPa)	Δp (kPa)	$\Delta p/p$	$p + \Delta p$ (kPa)	period (sec)
1'	49	216	4.4	265	83
2'	88	216	2.4	304	83
3'	118	216	1.8	333	83
4'	147	206	1.4	353	83
5'	196	196	1.0	392	83
6'	274	176	0.6	451	83
7'	353	147	0.4	500	83
8'	519	98	0.2	617	83
9'	137	255	1.8	392	83
10'	78	314	4.0	392	83

Fig. 7. Time-settlement curves under static and repeated loading (The loading period is constant)

we carried out repeated consolidation tests in which the loading period was kept constant. The loading sequences are shown in Table 3.

Figs. 7(a) and 7(b) show the result of our experiments in which the loading period was kept constant (83 sec) for any depth. There are some similarities between the loading period in Fig. 7 and the respective loading period in Fig. 3 which change in proportion to the depth, and the amount of settlement under repeated loading is larger than that under static loading, but the difference between these two types are small. It seems that the settlement of the sample varies according to the duration of the loading period. The resulting settlement amounts produced with changes of loading period are shown in Figs. 8(a) and 8(b). As is obvious from the figures, the settlement in the case of the long period of cyclic loading, is larger than in the case of the short period of cyclic loading as far as our present experiments are concerned.

Fig. 8. Time-settlement curves under static and repeated loading (The loading period is varied)

This phenomenon arises from the fact that pore water is kept at the drained condition under a static load, while under repeated loading the drainage and suction of pore water take place alternatively. A long period of cyclic loading affects even the inner layers of a sample, but a short period of cyclic loading affects the consolidation samples only to the depth of a thin layer near the surface of the samples. Hence it is clear that within the extent of our tests and at a constant load increment ratio $\Delta p/p$, the settlements in the case of the long period of cyclic loading are larger than those in the case of the short period of cyclic loading.

As in the case of the oil storage tank foundation, the difference in vertical strain varies with the depth under repeated loading and the difference in vertical strain is found to be larger than that of the deeper layer; thus, when at the layer shallower than -10 m the LIR is larger than 1, the difference in verti-

Fig. 9. Time-settlement curves under repeated loading, with varying load increment ratio

cal strain between static and repeated consolidations becomes large.

Consolidation tests under static and repeated loading were carried out for the purpose of investigating whether the LIR has an effect on the settlement under repeated loading, for the condition in which the total load $p + \Delta p$ is constant but the LIR $\Delta p/p$ is changed. These test results are shown in Fig. 9. Though the initial settlement resulting from the static pressure p is proportional to the magnitude of pressure, the total settlement is in proportion to the LIR. These results agree approximately with those in the tests carried out by Aboshi et al. (1981) within the LIR range of $\Delta p/p = 0.4 \sim 0.8$. As mentioned above, it can be concluded that the factors which affect the consolidation under repeated loading are the magnitude of total load, the loading period and the LIR.

It is well known that the mechanical properties of cohesive soils are affected by the initial soil particle structure. Recently there have been an increasing number of studies which take into consideration the effect of soil particle structure, such as anisotropy, in the establishment of constitutive equations for soils and the analysis of soil behavior. Fig. 10 shows the vertical strain versus the elapsed time curves obtained from repeated consolidation tests on one type of alluvial clay which has been categorized into different initial soil structures, such as flocculated structure or dispersed structure. Among them,

Fig. 10. Relationship between vertical strain and time in flocculated and dispersed clay structure on Ariake clay (Yamanouchi et al.)

Fig. 11. Influence of the initial soil particle structure and the consolidation method on the relation k and $e^3/(1+e)$ on Ariake clay (Yamanouchi et al.)

the untreated or natural sample was assumed to have developed with a random or flocculated structure because they were taken from a marine clay deposit. The dispersed-structure sample was one which had been prepared by treating clay slurry with tetrasodium phosphate. It was observed that the sample with flocculated structure exhibits a larger coefficient of secondary compression rate than that of the dispersed structure. Fig. 11 shows the relationship between the coefficient of permeability k measured on the samples after the consolidation tests were completed, and the values of $e^3/(1+e)$ are given. In this figure, the difference in gradient of the straight line shows how the method of loading and the change of soil particle structure are related to the initial structure. The following Kozeny-Carman equation was introduced as a method to of expressing quantitatively the change in soil particle structure during consolidation :

$$k = \frac{1}{k_0 S^2} \frac{e^3}{1+e} \quad (4)$$

where k is the coefficient of permeability, k_0 is a constant, S is the specific surface and e is the void ratio. The term $k_0 S$ will be used to represent the degree of tortuosity of flow and also the degree of orientation of the soil particles.

For the purpose of investigating the extent to which repeated loading has an effect on the samples, conventional oedometer tests were carried out on Kudamatsu clay after consolidation under static and repeated loading. Figs. 12(a) and 12(b) show the relationships between the LIR and the coefficient of consolidation c_v and the coefficient of volume compressibility m_v . Here, c_v and m_v are the average values obtained from standard consolidation tests (98-1254 kPa). For both c_v and m_v , the plots of the variations against LIR are a little scattered at each loading stage, and for this reason we can conclude that for both of these coefficients there is no difference in effect after static or repeated loading.

Fig. 13 shows the relationship between α and LIR, where α is the ratio of the yield

Fig. 12 (a). Relationship between coefficient of consolidation c_v and load increment ratio $\Delta p/p$

Fig. 12 (b). Relationship between coefficient of volume compressibility m_v and load increment ratio $\Delta p/p$

Fig. 13. Relationship between $\alpha = p'_y/p'_y$ and load increment ratio $\Delta p/p$

Fig. 14 (a). Relationship between total strain ε and number of load cycles N

Fig. 14 (b). Relationship between recoverable strain ε^e and number of load cycles N

stress in consolidation under repeated loading and that under static loading. Though the yield stress of consolidation in clay samples under static loading is nearly equal to $p + \Delta p$, the yield stress in the case of repeated loading is 1.1~1.2 times as large as that under static loading, where we calculate the yield stress in consolidation according to the SMFE committee proposal.

Figs. 14(a) and 14(b) show the relation between the number of load cycles and the total strain and the recoverable strain, respectively. As is well known, the strain of soil under repeated loading is composed of the unrecoverable strain ε^p and the recoverable strain ε^e . Fig. 15 shows the increase in strain for typical repeated consolidation tests. Hence, even in the case of repeated oedome-

Fig. 15. The increase in strain for typical repeated consolidation tests

ter tests, we can assume

$$\varepsilon = \varepsilon^e + \varepsilon^p \quad (5)$$

The total strain ε is proportional to the number of loading cycles (Fig. 14(a)), but the recoverable strain has a tendency to have an almost constant value after a certain numbers of load cycles (Fig. 14(b)). This inclination seems to be independent of the number of load cycles, and this constant value, as shown in Fig. 16, seems to be linearly proportional

Fig. 16. Relationship between recoverable strain ε^e and load increment ratio $\Delta p/p$

to the LIR or the repeated load Δp , to the extent of the experimental findings presented in this paper. It may be possible to make use of this result in the determination of a dynamic modulus of elasticity.

CONCLUSIONS

Oedometer tests under static and repeated loading have been made on saturated cohesive soils. The experimental results lead to the following conclusions :

1) The settlement caused by repeated loading is larger than that caused by static loading, and this difference originates or results from the predominant secondary compression during cyclic loading.

2) As in the case of an oil storage tank, the settlement caused by repeated loading is larger in the shallow layer than in the deep layer.

3) The factors influencing the settlement under repeated loading are concluded to be the magnitude of total load, the loading period, the load increment ratio and the initial soil particle structure.

4) The yield stress in consolidation of clay soil after being subjected to repeated loading is larger than that after static loading, and this difference seems to be caused by the change of soil particle structure.

5) The total strain is proportional to the number of load cycles, but the unrecoverable strain tends to have an almost constant value in relation with the number of load cycles after a certain number of cycles.

6) Besides the dependence upon the characteristics of the initial soil structure, the consolidation of clay under repeated loading is most the relevant factor in the rearrangement of soil particle structure.

Based on the experimental results, a settlement calculation was performed for the design of oil storage tank founded on soft clay. The importance of the repeated loading history is emphasized for settlement calculation involving soft clay, in comparison with consolidation settlement calculations carried out by means of the conventional method, using the Terzaghi theory of one-dimensional consolidation.

NOTATION

c_v = coefficient of consolidation
 D = length of drainage path of sample

e = void ratio
 m_v = coefficient of volume compressibility
 k = coefficient of permeability
LIR = load increment ratio
 p = static pressure
 Δp = vertical pressure
 p_y = yield stress in consolidation
 q = equivalent uniform load
 R = diameter of tank
 t_1 = the period of time required to fill the tank with oil and then to drain the tank completely
 t_2 = loading period
 T_v = time factor
 Z = depth
 ϵ = total strain
 ϵ^e = recoverable strain
 ϵ^p = unrecoverable strain
 ϵ_α = coefficient of secondary compression

REFERENCES

- 1) Aboshi, T., Yoshikuni, H. and Jinno, K. (1981) : "The consolidation characteristics of saturated clay subjected to repeated load," Preprint, 36th Annual Meeting, JSCE, Vol. 3, pp. 146-147 (in Japanese).
- 2) Andersen, K. H. (1976) : "Behaviour of clay subjected to undrained cyclic loading," Proc. Int. Conf. on Behaviour of Off-shore Structure, Trondheim, 1, pp. 392-403.
- 3) Bjerrum, L. (1966) : "Secondary settlement of structure subjected to large variations in live load," IUTAM, Symp. Rheology and Soil Mechanics.
- 4) Brown, S. F. et al. (1977) : "The effect of drainage on cyclic loading of clay," Proc. 9th ICSMFE, Vol. 2, pp. 195-200.
- 5) Hyde, A. F. L. and Brown, S. F. (1976) : "The plastic deformation of a silty clay under creep and repeated loading," Geotechnique, 26(1), pp. 173-184.
- 6) Kawakami, F. and Ogawa, S. (1965) : "Strength and deformation of compacted soil subjected to repeated stress application," Proc. 6th ICSMFE, Vol. 1, pp. 264-267.
- 7) Luo, W. K. (1973) : "The characteristics of soils subjected to repeated loads and their application to engineering practice," Soils and Foundations, Vol. 13, No. 1, pp. 11-27.
- 8) Sangrey, D. A., Henkel, D. J. and Esrig, M. I. (1969) : "The effective stress response of a saturated clay soil to repeated loading," Canadian Geotechnical Journal, 6(3), pp. 241-252.

- 9) Seed, H. B. and Chan, C. K. (1958) : "Effect of stress history and frequency of stress application on the deformation of clay subgrades under repeated loading," Proc. HRB, Vol. 37, pp. 555-575.
- 10) Seed, H. B., Chan, C. K. and Monismith, C. L. (1955) : "Effect of repeated loadings on the strength and deformation of compacted clay," Proc. HRB, Vol. 34, pp. 541-558.
- 11) Yamanouchi, T. and Luo, W. K. (1964) : "A method to relate repeated loading condition upon soil specimen with deformation," Paper, 2nd Pacific Regio. Conf., IRF, 10 pp.
- 12) Yamanouchi, T. (1970) : "Experimental study on the improvement of the bearing capacity of soft ground by laying a resinous net," Proc. Symp. Foundations on Interbedded Sands Div. of Applied Geomech., CSIRO and Western Group, Aus. Geomech. Soc., pp. 144-150.
- 13) Yamanouchi, T., Fujiwara, H. and Yasuhara, K. (1971) : "Consolidation characteristics of alluvial clay under repeated loads," Tech. Report of Kyushu University, Vol. 44, No. 4, pp. 499-504 (in Japanese).
- 14) Yamanouchi, T. and Yasuhara, K. (1975) : "Settlement of clay subgrades of low bank roads after opening to traffic," Proc. 2nd Aus. and NZ, Conf. Geomech., Vol. 1, pp. 115-120.
- 15) Yasuhara, K. et al. (1981) : "Consolidation of undisturbed soft clay under cyclic loading," Preprint 36th Annual Meeting of JSCE, Vol. III, pp. 148-149 (in Japanese).
- 16) Yasuhara, K., Yamanouchi, T., Fujiwara, H., Aoto, H. and Hirao, K. (1983) : "Approximate prediction of soil deformation under drained repeated loading," Soils and Foundations, Vol. 23, No. 2, pp. 13-25.
- 17) Yasuhara, K. : "Undrained and Drained Cyclic Triaxial Tests on a Marine Clay," Proc. 11th ICSMFE.
- 18) Yasuhara, K. et al. (1980) : "Simplified strain-time relations for clay under cyclic loads," Proc. Inter. Symp. Cyclic and Transient Loading of Soils.