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# Consolidation in clays due to cyclic stresses

## Consolidation des argiles due aux contraintes cycliques

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**SYNOPSIS :** A series of tests were performed to evaluate the influence of cyclic loading on consolidation behavior of clays. The samples consolidated incrementally to a specific axial stress level were subjected to cyclic shear stresses under undrained conditions and settlements due to dissipation of accumulated excess pore water pressure were determined.

### 1 INTRODUCTION

The behavior of clays during and after cyclic loading has been studied by large number of researchers up to the present. Some of the early investigations reported in the literature were performed by Seed & Chan (1966), Thiers & Seed (1968). In these studies stress-strain and strength properties of clay samples were evaluated based on cyclic triaxial and cyclic simple shear tests. Another group of study reported in the literature were performed by Sangrey, Henkel & Esrig (1969), France & Sangrey (1977), and Sangrey & France (1980). In these investigations the cyclic stress-strain-pore water pressure behavior of clays are studied based on cyclic triaxial tests performed at relatively slow rates under undrained and drained conditions. The cyclic behavior of clays are also studied by other researchers as Andersen, et al. (1980), Wood (1980), Koutsoftas & Fisher (1980), Matsui, Ohara, & Ito (1980), Dyvik, Zimmie, and Schimelfenyg (1983), Goulis, Whitman, & Hoeg (1985), Ishihara (1980, 1985). All of these studies were based on laboratory investigations of clay behavior and mostly concerned with cyclic stress-strain and shear strength properties during and post cyclic loading.

In this study a different aspect of clay behavior is studied. The main purpose is to investigate the consolidation phenomena arising from the dissipation of the excess pore water pressures developed in cohesive soils subjected to cyclic shear stresses. In horizontally layered cohesive soils, cyclic shear stresses generated during earthquakes, may not lead to major stability problems (Ishihara, 1980, 1985). However, these cyclic shear stresses would trigger an increase in pore water pressures which would dissipate afterwards (Wilson and Greenwood, 1974; Andersen, et al., 1980) and may induce settlements. These generally emerge as consolidation settlements which would take place during the post earthquake dissipation of the excess pore water pressures accumulated under cyclic loading during earthquakes in saturated soil layers.

In order to study the significance of the magnitude and the effect of various factors on settlements induced by cyclic loading, series of tests were performed on undisturbed natural clay samples. The samples were consolidated incrementally up to stress levels according to selected overconsolidation ratio and were subjected to cyclic shear stresses under undrained conditions for a specific number of cycles. The pore water pressure accumulation and cyclic shear strain variations were monitored. Following the cyclic loading, drainage is allowed and consolidation settlements are recorded. The main purpose was to examine the effects of cyclic shear stress amplitude, number of cycles, and overconsolidation ratio on settlements induced by pore water pressure dissipation.

### 2 TESTING PROCEDURE AND RESULTS

The testing programme was carried out in Soil Dynamics Laboratory of Civil Engineering Faculty at Istanbul Technical University using Dynamic Simple Shear Testing System. The samples were obtained from boring operations carried out in two areas in Istanbul. The first group of samples were taken from (plastic) fat silty clay (CH) layer located on the sea floor in Golden Horn. The second group of samples were taken from the lean organic silty clay (CL/OL) layer encountered at Baltalimanı on the north side of Bosphoros.

The samples tested were 70 mm in diameter and 30 mm in height. They were placed in the simple shear cell and were consolidated incrementally in accordance with conventional procedure under  $K_0$  conditions to axial stresses larger than preconsolidation stress determined from odometer tests. At this stage a back pressure of 400 kPa and confining pressure of 410 kPa are applied to assure saturation. In order to obtain the desired overconsolidation ratio, OCR, the samples were unloaded incrementally to selected stress levels. After the completion of consolidation or swelling at this stage, the samples were subjected to cyclic shear stresses under undrained conditions for a

specific number of cycles. Following the cyclic loading, drainage valves were opened and excess pore water pressures were allowed to dissipate while monitoring the settlements in the samples. After a period of 24 hours and upon termination of axial strains, the samples were loaded incrementally to 800kPa consolidation pressure in a similar way as in conventional consolidation tests.

In the first phase of this investigation the effect of cyclic loading on excess pore water pressure buildup and resulting settlements were studied with respect to overconsolidation ratio. For this purpose undisturbed Golden Horn clay samples were consolidated incrementally to stress levels higher than the preconsolidation stress determined from conventional consolidation tests and were unloaded to achieve desired overconsolidation ratios (OCR = 1,3,5). After reaching the desired loading stage, the samples were subjected to cyclic shear stresses with amplitudes equal to 50% of undrained shear strength for 50 cycles at a frequency of 0.1 Hz under undrained conditions. In order to make an appropriate comparison the axial consolidation pressures at the stage of cyclic loading were kept identical for all of the samples. The undrained shear strengths were also determined in the same simple shear testing system by quasi-static stress controlled procedure and under undrained conditions.

The results obtained from one such test where OCR = 3 at the stage of cyclic loading is shown on Figure 1 in conventional form in terms of void ratio,  $e$ , versus log of effective axial stress,  $\log p'$ .

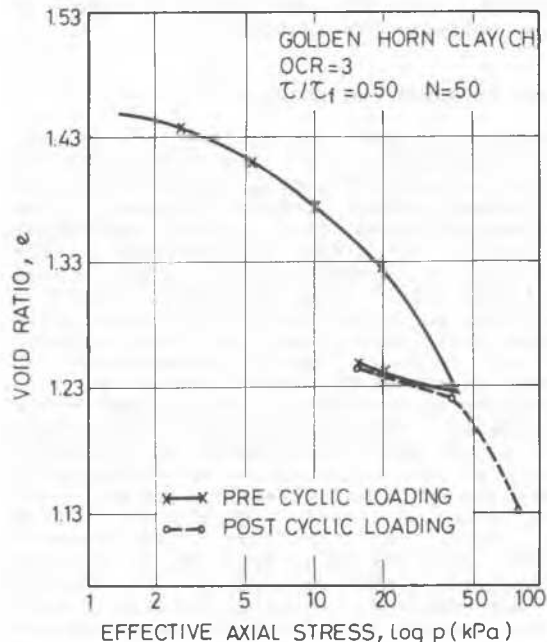


Figure 1. The effect of cyclic loading on consolidation of overconsolidated clays

As can be observed from this figure, the magnitude of accumulated pore water pressure were relatively small and as a result the corresponding settlements remained negligible and there appears to be no significant effect of cyclic loading on the consolidation response of the sample. Similar results were also obtained for other samples with OCR > 1. This type of response was anticipated since prior tests on overconsolidated clays have shown similar pore water pressure response patterns (Andersen, et al., 1980).

The results obtained from tests on normally consolidated samples (OCR = 1), have shown a different trend (Lo, 1969; Matsui, Ohara, & Ito, 1980). In these samples the level of accumulated pore water pressures were higher and the resulting settlements became more significant. As can be seen in Figure 2, the magnitude of additional decrease in void ratio due to cyclic loading may yield important additional settlements for thick normally consolidated layers of clay deposits.

The second phase of the study was carried out only on normally consolidated clay samples since the above summarized results have shown that consolidation settlements post cyclic loading is insignificant for overconsolidated clays. The remaining two primary factors controlling settlements are the number of cycles and cyclic shear stress amplitude. First the effect of the number of cycles applied to the samples were studied based on tests conducted on similar samples consolidated to the same axial pressure and subjected to the same cyclic shear stress amplitude. The response patterns obtained in one set composed of three tests conducted at different number of

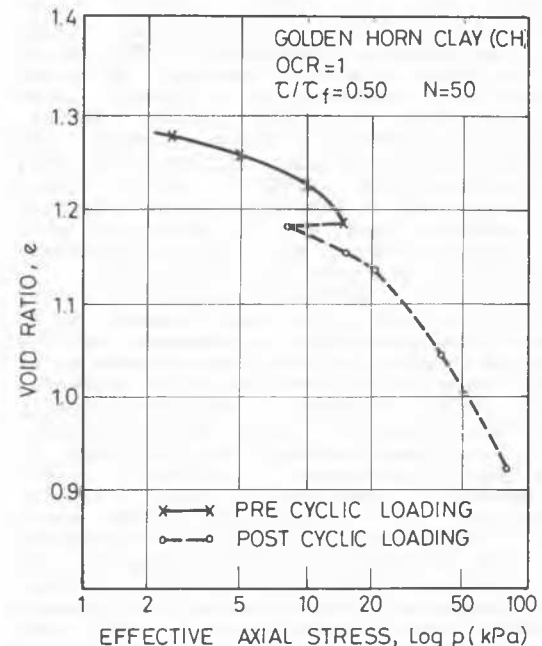


Figure 2. The effect of cyclic loading on consolidation of normally consolidated clays

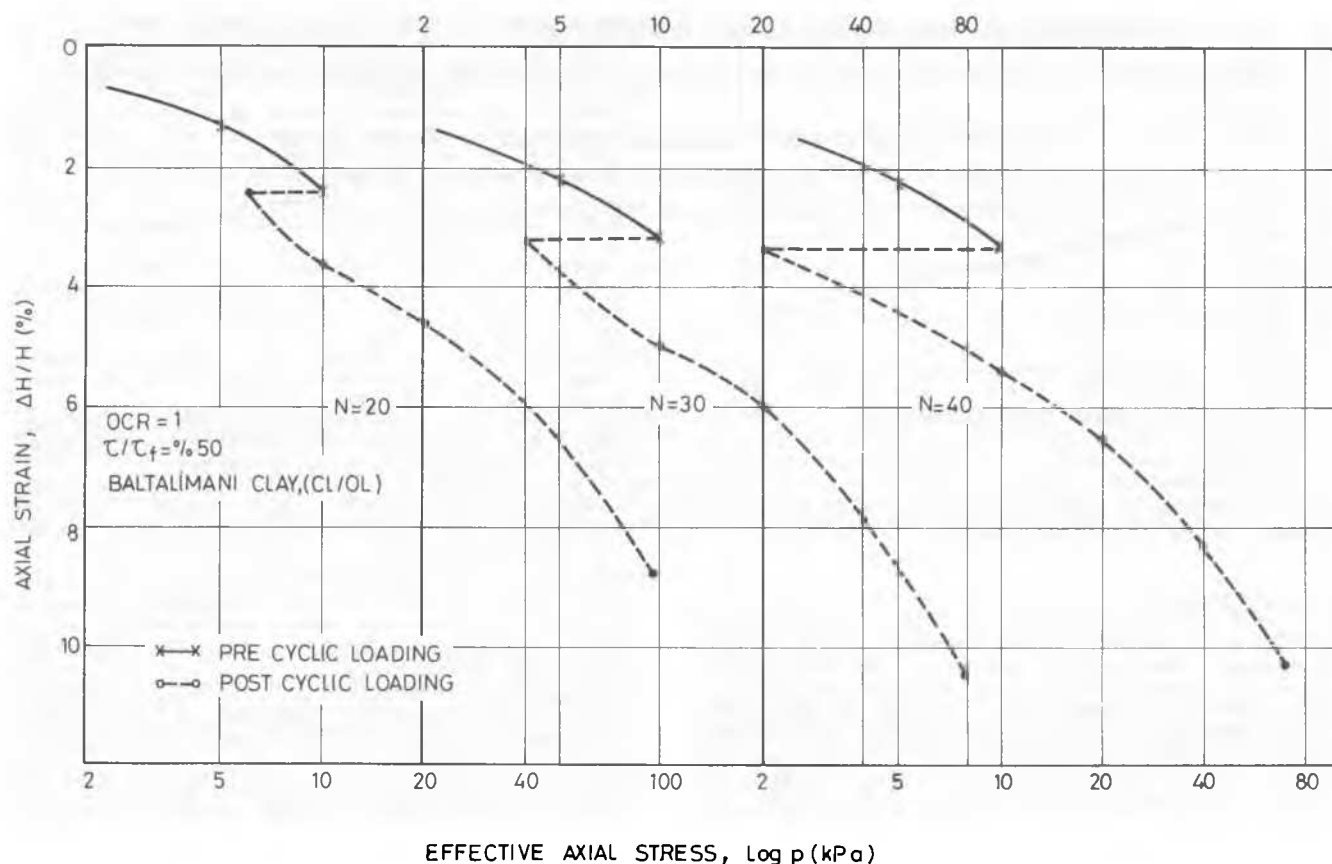


Figure 3. The effect of number of cycles on consolidation settlements

cycles are shown on Figure 3. As anticipated the increase in the number of cycles leads to an increase in accumulated excess pore water pressure and as a result in observed axial strains.

In order to demonstrate the influence of number of cycles, the variation of axial strain with respect to number of cycles is given in Figure 4 on a semi-logarithmic scale. A linear relationship seems to be valid for the range of tests carried out. Under these conditions, by adopting such an approach based on three such cyclic simple shear tests, it appears possible to estimate the magnitude of axial strains after an expected earthquake if equivalent number of cycles is specified.

The other factor influencing the pore water pressure buildup and resulting settlements is the magnitude of the cyclic shear stress amplitude. In order to be able to generalize the findings, the cyclic shear stress amplitudes were normalized with respect to undrained shear strength determined in the same testing system for the similar sample under the same consolidation pressure. A set of tests were performed where similar samples consolidated under same axial stress level were subjected to different amplitudes of cyclic shear stress expressed in terms of normalized cyclic stress ratio for identical number of cycles. The observed settlements as shown on

Figure 5 appears to vary linearly with respect to cyclic stress ratio in a semi-logarithmic scale. This approach based on three cyclic simple shear tests performed at specified equivalent number of cycles but for different cyclic shear stress amplitudes may be also be utilized to estimate the order of expected settlements after a probable earthquake.

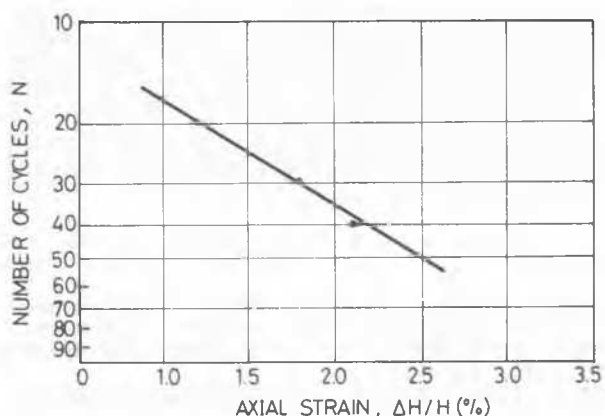


Figure 4. The variation of settlements with respect to number of cycles

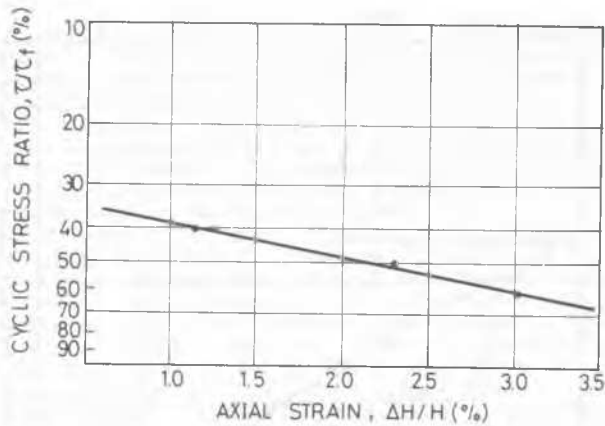


Figure 5. The variation of settlements with respect to cyclic stress ratio

### 3 CONCLUSIONS

The results briefly summarized in this paper indicates that cyclic shear stresses applied to normally consolidated clay samples may lead to additional settlements due to the dissipation of accumulated excess pore water pressures. However, for overconsolidated clay samples since the pore water pressure buildup is relatively small no significant effect of cyclic loading was observed on consolidation response.

The undisturbed clay samples tested were obtained from two different sites in Istanbul where one group consisted of fat silty clay (CH) and the others were lean organic silty clay (CL/OL) samples. Sets of tests were performed to study the effect of number of cycles and cyclic shear stress amplitude on the observed settlements occurring due to the dissipation of pore water pressure. In both cases a semi-logarithmic linear relationships would be useful to estimate the magnitude of settlements based on number of cycles and cyclic shear stress amplitudes. The results reported in this paper is part of the preliminary findings obtained from a research conducted on the effect of cyclic loading on consolidation phenomena. The results obtained up to the present have shown the importance of the magnitude of settlements, however, no significant difference became apparent between different types of clay and silty clay samples with different index properties.

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