Effect of cyclic loading on recompression of overconsolidated clay
L'effet des chargements cycliques sur la recompression des argiles surconsolidées

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SYNOPSIS: The current paper aims at providing fundamental information about calculation of settlement of offshore gravity platforms on overconsolidated clay due to dissipation of cyclically induced pore pressure. The cyclic direct simple shear testing apparatus was used to simulate a series of storms separated by drainage between the storms. It was concluded that the post-cyclic recompression settlements of overconsolidated clay could approximately be estimated by using the recompression index in oedometer tests. It was also indicated that the compressibility for load beyond the initial consolidation stress was dependent on the cyclic shear strain and cyclically induced pore pressure.

INTRODUCTION

Offshore gravity platforms will be subjected to a number of storms which will generate excess pore pressures in the soil. For platforms on clay, no significant drainage will occur during one individual storm. During the calmer period between successive storms, however, the pore pressures generated by cyclic loading may dissipate. Cyclic loading accompanied by dissipation of the cyclically induced pore pressure may give settlement in addition to that occurring under purely static load. It may also influence the soil behaviour during later storms.

A laboratory program was carried out using the NGI direct-simple shear apparatus on an over-consolidated clay. The tests simulated a series of storms (represented by undrained cyclic loading) separated by drainage between the storms. The cyclic direct-simple shear (DSS) test is considered to simulate closely the stress conditions in soil elements beneath the centre of offshore gravity structures. The following aspects are discussed in this paper:

a) The effect of drainage between storms on behaviour during subsequent undrained cyclic loading.

b) How the volumetric deformations due to the dissipation of cyclically induced pore pressure are related to the magnitude of the induced pore pressure. These volumetric deformations are compared to the volumetric deformations in oedometer specimens that were unloaded by an amount equal to the cyclically induced pore pressure and then recompressed.

c) The compressibility for subsequent consolidation past the initial overburden pressures. Additional pressures were applied to both the DSS and the oedometer specimens until the vertical pressure was three times the initial vertical consolidation pressure.

EXPERIMENTAL PROGRAMME

The tests were run on plastic Drammen clay because a large number of cyclic tests have been carried out on this clay previously (Andersen et al., 1980 and 1988). Average index properties are: natural water content w_n = 52%, liquid limit w_L = 55%, plasticity index I_P = 27, and specific gravity G_s = 2.76. In the cyclic DSS tests used for the present study, a circular specimen with 35cm^2 area and 16mm initial height was consolidated in several increments up to 392 kPa (normally consolidated clay) and was then swelled back to consolidation stresses of 98, 39 or 9.8 kPa to produce overconsolidated clays with OCR = 4, 10 and 40, respectively. One or five consecutive series of undrained cyclic loading with subsequent drainage were applied. The number of load cycles was on the average 100 cycles for each series. The cyclic load period was 10 seconds. The testing programme was schemed to contain various cyclic shear stress levels, τ_{hcy}/τ_{sf} (τ_{hcy} : horizontal cyclic shear stress, τ_{sf} : maximum horizontal shear stress in static DSS tests).

The loading sequences are illustrated in Fig. 1. After the loading with one or five series of cyclic loading, four of the specimens were consolidated to higher vertical effective stresses to study the effects of cyclic loading on the subsequent consolidation properties of the specimens. Four other tests were subjected to undrained static loading after the cyclic

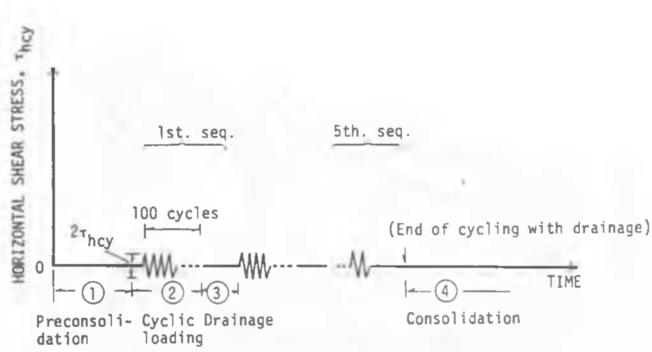

Fig. 1 Loading sequences of cyclic DSS test with drainage

loading. In addition to the cyclic tests, a consolidation test with five series of loading, unloading and reloading histories was also run in the DSS apparatus for comparison with recompression behaviour during dissipation of the cyclically induced pore pressure.

DETERIORATION OF OVERCONSOLIDATED CLAY DUE TO CYCLIC LOADING AND DRAINAGE

Typical results from two cyclic DSS tests on overconsolidated clay (OCR = 4) with drainage are presented in Figs. 2 and 3. The cyclic horizontal stress was τ_{hcy} = 31 kPa corresponding to 45% of the horizontal shear stress at failure in an undrained static test.

The results in Fig. 2 are from a DSS test with 5 periods of undrained cyclic loading, the first three periods each consisting of 100 cycles. Drainage was included after each period of cyclic loading. The duration of the drainage periods was 60 min for this test.

During the first 100 cycles, a mean pore pressure of 32 kPa developed (Fig. 2). This is about 33% of the vertical effective consolidation stress. However, the pore pressure generation increased with successive cyclic loading periods. The pore pressure reached 50% of the vertical consolidation stress at the end of the 2nd period and 54% at the end of the 3rd period. In the 4th period the pore pressure

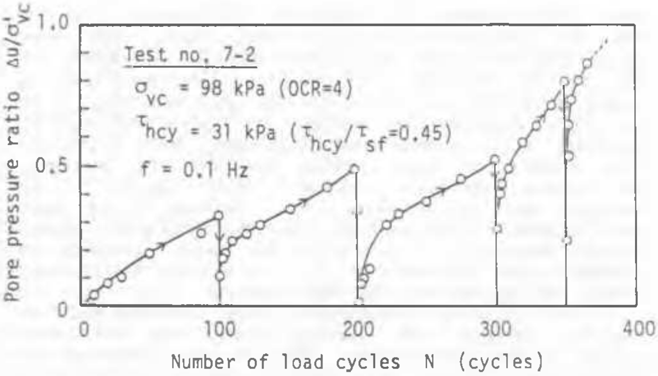

Fig. 2 Results from cyclic DSS test no. 7-2 with drainage

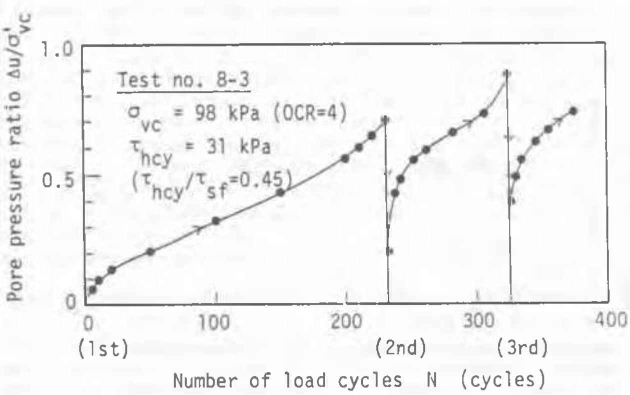

Fig. 3 Results from cyclic DSS test no. 8-3 with drainage

reached 81% after 40 cycles. For this specimen the cyclic shear strains were also significantly influenced by the preshearing. In the 4th period of cyclic loading the cyclic shear strains increased substantially, and after 40 cycles a cyclic failure (3% cyclic shear strain) was about to develop. The cycling was then stopped to avoid a complete failure and drainage was permitted before the 5th cyclic loading was applied. In the 5th period the specimen suffered a complete failure after only a few cycles in spite of the previous drainage.

The results from the second test are shown in Fig. 3. In this test the duration of each drainage period was 24 hrs. Cyclic loading was in the first period applied until the specimen was near failure (234 cycles). Then drainage was permitted. The pore pressure and the shear strain increased much faster in the 2nd cyclic loading than in the first, and after about 70 cycles in the 2nd period, a complete failure was about to develop.

The two tests in Figs. 2 and 3 indicate that cyclic loading accompanied by drainage may have a deteriorating effect on overconsolidated clays and lead to lower resistance to subsequent undrained cyclic loading. The number of cycles to failure would be about 240 - 250 if the clay had not experienced cyclic loading and drainage. The clay failed after 70 cycles when it had first been subjected to one period with 234 cycles and drainage (Fig. 3), and it failed after 40 cycles when it had first been subjected to three periods with each 100 cycles and drainage (Fig.2). This behaviour of overconsolidated clay is different from the behaviour of normally consolidated clay which gets stronger if it is first subjected to periods of cyclic loading and drainage (Andersen, 1976, Yasuhara and Andersen, 1987a).

POST-CYCLIC RECOMPRESSION

As drainage takes place after application of cyclic loading, the cyclically induced pore pressure will dissipate, and recompression settlements will occur. The permanent pore pressure generated by undrained cyclic loading will lead to a reduction in effective normal stress. This corresponds to going from point A to point B in the load-settlement plot in Fig. 4a. As drainage occurs and the excess pore pressure dissipates, the effective normal stress increases again, and it seems reasonable to assume that the soil element will recompress following a conventional reloading curve in an oedometer type of test.

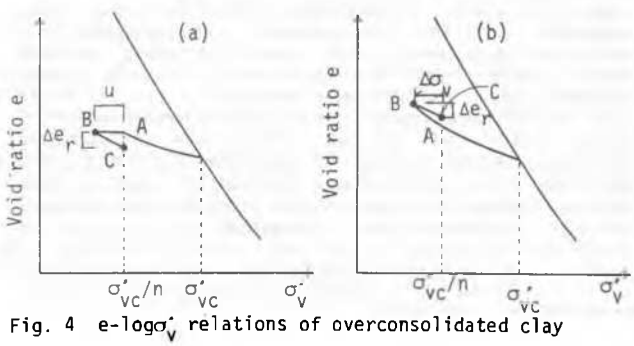

Fig. 4 e-logσ'_v relations of overconsolidated clay

a) post-cyclic recompression in DSS test

b) recompression in consolidation test

At point C in Fig. 4a, the effective stress reaches the same value as before start of cyclic loading. This means that one should investigate the similarity of recompression behaviour between the reloading branch in a conventional oedometer test (Fig. 4b) and the post-cyclic recompression branch (Fig. 4a). If they are the same, it will be possible to predict the recompression volumetric strain due to dissipation of cyclically induced pore pressure based upon recompression data from conventional oedometer tests.

Fig. 5 shows the e-logσ'_v paths for the Test No. 7-2, during both undrained cyclic loading and the subsequent consolidation. The results from tests on normally consolidated specimens indicated that the cyclically induced pore pressure decreases for each series of cyclic loading, and the reduction in void ratio during the subsequent pore pressure dissipation becomes smaller after each series (Andersen et al., 1976; Yasuhara and Andersen, 1987a and 1987b). For the overconsolidated specimen, the tendency is opposite. As shown in Fig. 5, the cyclically induced pore pressure increases for each series of cyclic loading, and the change in void ratio during the subsequent pore pressure dissipation increases.

For comparison with post-cyclic recompression behaviour and to produce data for predicting volumetric strains due to dissipation of cyclically induced pore pressure, one oedometer type consolidation test was conducted in the DSS apparatus. It was attempted in this test to apply the load history observed in the cyclic DSS test in Fig. 5 as closely as possible. The result from this test is presented in Fig. 6 in the form of e-logσ'_v paths.

It seems reasonable to assume that the post-cyclic recompression volumetric strain could be estimated using the recompression index C_r obtained from this oedometer type test with five series of loading, unloading and reloading. Fig. 7 illustrates that there is good agreement between the recompression volumetric strain measured in the cyclic DSS test and the one calculated by the relation:

$$\varepsilon_{vr} = \frac{C_r}{1+e_c} \log\left(\frac{1}{1 - u/\sigma'_{vc}}\right) \qquad (1)$$

where e_c is the void ratio at the start of cyclic loading and C_r was determined from the oedometer data in Fig. 6. The C_r-value depends on the number of reloadings that have been applied. The calculations are therefore made with the C_r-values for the reloading number that corresponds to the cyclic recompression number.

However, a comparison from the two tests indicates one important difference. In the oedometer-type test significant swelling occurs during unloading. In the cyclic test the decrease in effective stress takes place under undrained conditions, and therefore no swelling occurs. The accumulated settlement due to a number of cyclic load series may therefore be significantly greater than for the same number of static unloading/reloading histories in an oedometer-type test.

COMPRESSIBILITY FOR SUBSEQUENT CONSOLIDATION PAST THE INITIAL CONSOLIDATION STRESSES

After the series of cyclic loading and drainage

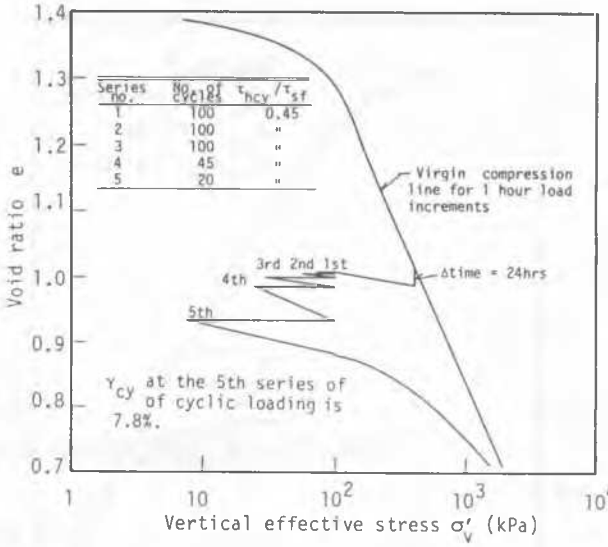

Fig. 5 e-logσ'_v paths of O.C. clay with cyclic loading and drainage

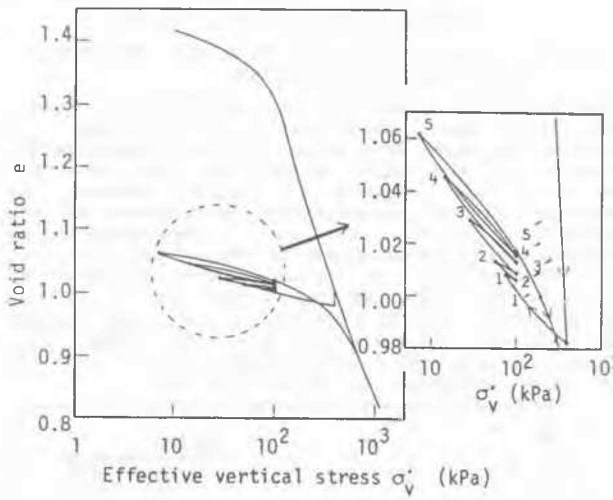

Fig. 6 e-log σ'_v relations of O.C. clay in oedometer test

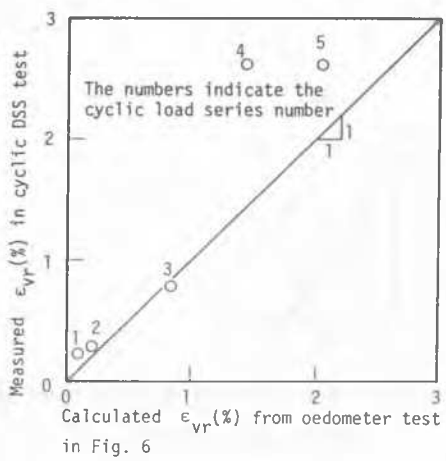

Fig. 7 Observed and calculated post-cyclic recompression volumetric strain in test (No. 7-2)

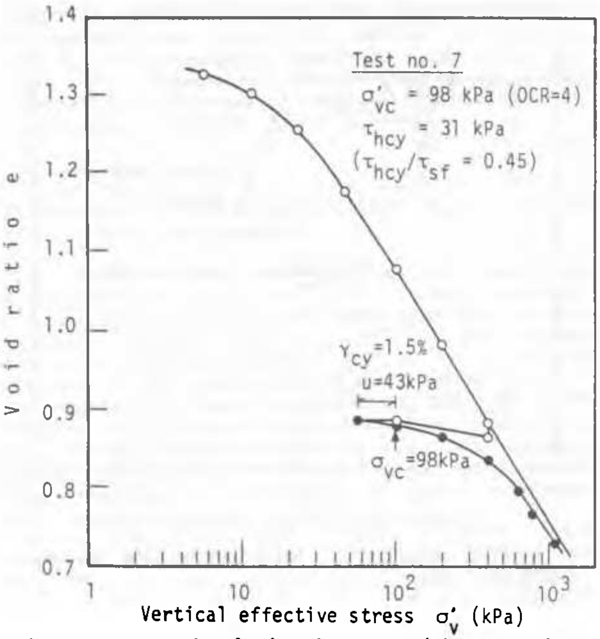

Fig. 8 e- log σ'_v relation for test with one series of cyclic loading with drainage

were completed, most of the specimens in cyclic DSS tests were consolidated to vertical effective stresses in excess of the consolidation stresses at the start of cycling. This was done to study the effects of cyclic loading and drainage on the consolidation properties of the specimens during further consolidation. An example was already given in Fig. 5 for the test with five series of cyclic loading followed by drainage. By comparing Fig. 5 and Fig. 6 it can be seen that cyclic loading and drainage caused the clay to approach and join the virgin consolidation line (NCL) much slower than if it had not been subjected to cyclic loading.

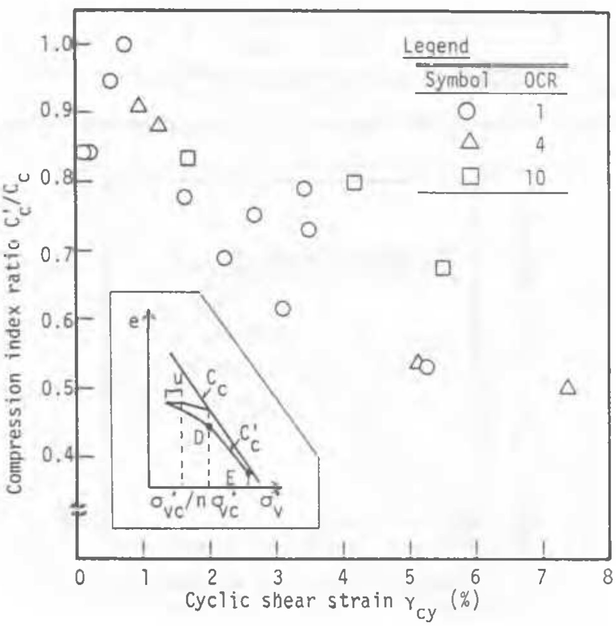

Fig. 9 Compression index in tests with cyclic loading with drainage

Fig. 8 presents an example of an e-logσ'_v path obtained from tests with one series of cyclic loading on an overconsolidated specimen with OCR= 4. In general, it was observed from tests like those in Figs. 8 and 5 that the larger cyclic shear strain the specimen has experienced, the slower it will return to the normally consolidated line. However, it does never proceed in parallel with the branch of normally consolidated clay in the e-log σ'_v plots. The ratio between the compression index after cyclic loading, C'_c, and the virgin compression index, C_c, was read out from the e-log σ'_v paths. C'_c is determined from the gradient of a line connecting point D at σ'_{vc} and point E at $3\cdot\sigma'_{vc}$ in Fig. 9. The ratio C'_c/C_c was plotted against the cyclic shear strain at the end of cyclic loading in Fig. 9. The results from normally consolidated specimens have also been included in Fig. 9.

It can be seen from Fig. 9 that the compression index of specimens with cyclic loading and drainage decreases with the magnitude of the cyclic shear strain. The ratio C'_c/C_c seems to decrease with increasing overconsolidation ratio, but this effect is somewhat uncertain due to the scatter in the data.

CONCLUSIONS

1) Cyclic loading and drainage may deteriorate overconsolidated clay and make it less resistant to subsequent undrained cyclic loading.
2) Recompression settlements will occur when cyclically induced pore pressures dissipate. The post-cyclic recompression followed the same reloading consolidation curve as an oedometer test subjected to the same number of vertical unloading/reloading stress histories as in the cyclic DSS test. However, the settlements accumulated after a number of cyclic load series may be significantly greater than after the same number of static unloading/reloading histories in an oedometer test.
3) The compression index for consolidation past the initial consolidation stress decreased with increasing values of cyclic shear strain and cyclically induced pore pressure.

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