Journal of Engineering and Applied Sciences 1(4): 375-382, 2006
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The Behaviour of Undrained Saturated Clay under Cyclic Loading

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Abstract: The work reported in this paper is about the behaviour of clay under cyclic triaxial loading. 102 mm high x102 mm diameter samples of remoulded undrained Cowden clay were used. In order to achieve accurate pore water pressure measurements and to gain some understanding in terms of effective stress of the fundamental behaviour of the saturated clay under cyclic loading, slow reversed load controlled cyclic tests were performed. In order to investigate the effects of undrained cyclic loading on the undrained shear strength, the cyclically loaded samples were subjected to post-cyclic monotonic loading. This investigation also examines the effects of the mean total stress variation on the clay's behaviour.

Key words: Clay, cyclic loading, undrained, shear strength, creep, ktress path, mean total stress

INTRODUCTION

The behaviour of clay subjected to cyclic loading is important in the foundation design of offshore gravity platforms. Wave action on offshore gravity platforms causes a great number of large cyclic horizontal forces and moments which are transmitted to and carried by the soil foundation. Extensive programs of laboratory tests have been carried out by numerous researchers[1-6]. They investigated the effects of cyclic loading on clay in the triaxial and simple shear apparatus and found that the behaviour of clay depends upon a wide range of factors, including the type of test, wave form, frequency, number of cycles and stress history. The deformations occurring during an earthquake can be induced by a cyclic loading triaxial test with a varying confining pressure[1]. An increase in pore water pressure softens a clay sample during cyclic loading. The cumulative increase in pore water pressure will cause a reduction in effective stress and, consequently, a reduction in undrained shear strength will occur[7-9]. However, beneath gravity-type offshore structures with large foundations, the drainage paths for excess pore pressure dissipation are comparatively long. As storms last several hours, even days, considerable excess pore water pressure may develop as a result. Accordingly, it is reasonable and conservative to assume completely undrained conditions. Although accurate pore water pressure measurements are of paramount importance for a better understanding of the behaviour of clay under cyclic loading, few studies of clay soils have included accurate measurement of pore water pressure, because of the low permeability of clays and the corresponding long response time for pore water pressure measurement. In the present investigation, load-controlled cyclic triaxial tests on undrained samples of Cowden clay were carried out. In order to gain some understanding of the fundamental behaviour of the saturated clay in terms of effective stresses, the acquisition of accurate pore pressure measurements throughout each cycle has been one of the major objectives of this investigation. For this purpose a low frequency of approximately 1cycle/hour has been used. Conventional reversed load-controlled triaxial tests are normally carried out by axial load at constant cell pressure. This leads to cyclic variation in the mean effective stress. In order to investigate the effects of the variation of the mean effective stress, the axial loads and cell pressures are cycled in and out of phase during the last cycle of each cyclic test. Cyclic loading of soil samples may result in softening so that the stress-strain properties are altered. To investigate this, samples (used for cyclic loading) were reloaded statically under displacement-controlled conditions to determine any strength loss caused by the cyclic loading.

EXPERIMENTAL APPARATUS AND PROCEDURES

The main laboratory equipments used in this research consisted of a conventional 102mm diameter sample triaxial cell, a conventional triaxial loading machine, an electro-servo hydraulic system and a cyclic cell pressure apparatus. To ensure as uniform a distribution of radial strains as possible throughout the sample, frictionless

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Table 1: Cyclic loading tests

Test code	U_{M0}	U_{B0}	Cu	τ/Cu		σ_0'		(ϵ_{da})max
	kN/m^2	kN/m^2	kN/m^2	Comp-ression	Ten-sion	kN/ m^2	OCR	(%)
A.1	323.3	330.8	70	0.3	-0.46	67.7	5.9	5
A.2	320.3	316	"	0.3	-0.46	79.7	5	1.5
A.3	304.2	300.5	"	0.3	-0.46	95.6	4.2	1.0
B.1	334.1	333.2	"	0.4	-057	67.1	6.0	5
B.2	320.3	315.3	"	0.4	-057	79.7	5	2
B.3	323.7	322.9	"	0.4	-057	76.3	5.2	2
B.4	323.9	323.3	"	0.4	-057	76.1	5.2	2
B.5	320.6	302	"	0.4	-057	97.4	4.1	2
C.1	318.6	317.3	"	0.59	-059	81.4	4.9	5
C.2	327.5	317.3	"	0.59	-059	72.5	5.5	5
C.3	318.7	317.3	"	0.59	-059	81.3	4.9	5
C.4	315	314.3	"	0.59	-059	85	4.7	5

Table 2: Monotonic tests on cyclically loaded samples

Test code	U_{M0} (kN/m^2)	U_{B0} (kN/m^2)	σ_0' (kN/ m^2)	OCR
B.1.C	360..8	362.1	33.8	11.8
B.2.C	348.1	346.5	45.5	8.8
B3.C	346.5	348.5	46.7	8.
B.4.C.	340.9	340.1	53.6	7.5
B.5.C	335.5	338.5	63.8	6.3
C.1T	369.3	369.3	29.8	13.4
C.2C	368.1	365.7	30	13.3
C.3.C.	376	374.9	24.1	1.6
C.4.C	376.5	373.7	22	18.2

end platens were used[10]. The electro-servo hydraulic system is composed of a hydraulic power supply, an actuator containing both a load cell and L.V.D.T. (Linear variable differential transformer) controlled by a servo valve and an electronic control console. Monotonic tests were carried out using a testing machine designed by "Wykenham Farrance Ltd.".

For the purpose of this research, an apparatus capable of cycling the cell pressure has been designed by the author. The main features of the apparatus were an electric motor, a gear box and a rotating arm holding a self-compensating mercury pot which is connected to a static pot. The system (mercury pot and arm) is driven by a small electric motor via a gear box. The motor has a constant speed of 0.5 revolution/minute. By sliding both the mercury pot and the counterweight along the arm a large range of amplitudes of sine wave form could be obtained (the amplitude can be varied from 0 to about 200 kN/m^2 and the frequency from 1/60 to 1/60.000 Hz). The principal of operation of the rotating mercury system is the same as that of the self-compensating mercury system described by Bishop and Henkel[11]. Bell and Howell transducer was used for cell pressure and base sample pore pressure measurements. The mid-height pore water pressure measurements were made by means of a miniature pressure transducer[12] developed by Druck Ltd.

Soil description: Cowden clay was used in this investigation. It is a glacial Till, dark brown in colour, obtained from the Cowden site on north Humberside. The index properties, as reported in reference[13], are as follows: Liquid limit = 44%; Plastic = 19%; Plasticity index = 25%; Clay fraction (D<0.002 mm) = 32%; Activity = 0.78; C_V of remoulded soil (σ_V' = 480kN/m^2) = 1.5m^2/yr. One final consolidation pressure of 600kN/m^2 was used for preparing remoulded samples of Cowden clay. The preparation procedure was as described below. The vertical consolidation pressure was applied by means of hydraulic pressure. The cell allowed top and bottom drainage. The pressure was applied in increments (ΔP/p = 1.0) up to the finale required pressure. After completion of the consolidation process, eight 102 mm internal diameter sampling tubes were extracted from the bed of clay.

Testing programme: Undrained cyclic triaxial tests were performed on remoulded Cowden clay. The clay was normally consolidated in a œdometer to a pressure of 600 kN/m^2. Three sets (A.B.C) of load-controlled triaxial tests were carried out at a frequency of 0.00027Hz (Table 1). Samples of series B and C were subjected to monotonic (compression or tension) loading after termination of cyclic loading. Details of these tests are given in Table 2. It shoud be noted that the last letter in the test code in Table 2 reffers to the type of loading (i.e., C for compression abd T for tension)

RESULTS AND DISCUSSION

Axial strain: The author believes that, due to the difference in the initial effective stress (σ_o') from one sample to another , resulting from the sample preparation process, as shown in Table.1, the best data interpretation may be on the basis of (τ /σ_o')$_{mean}$.

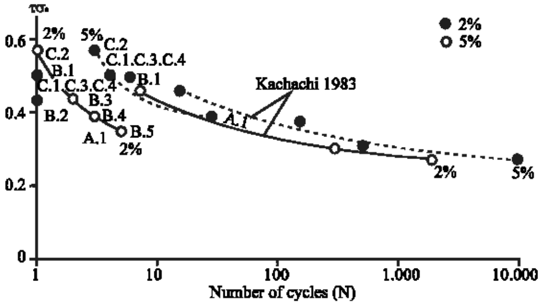


Fig. 1: τ / σ_0' versus s number of cycles for all cyclic tests

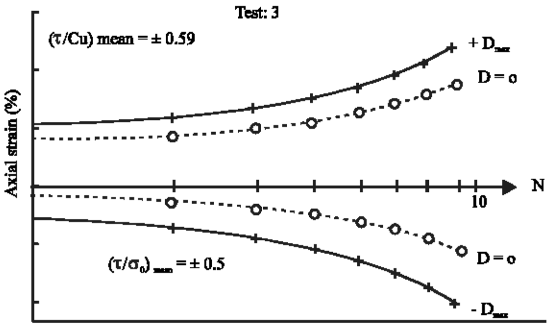


Fig. 2: Axial strain versus number of cycles for test C.3

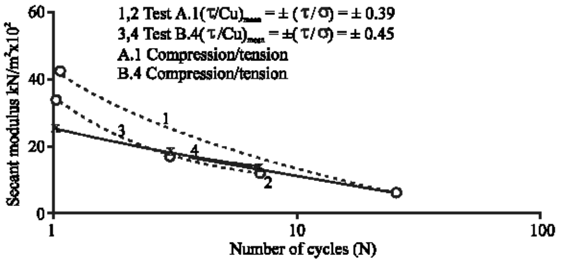


Fig. 3: Secant modulus versus number of cycles for tests series A. and B

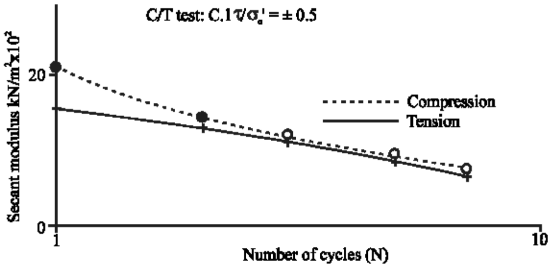


Fig. 4: Secant modulus versus number of cycles for tests C1

The parameters τ /Cu and τ/σ_0 are the ratios of maximum shear stress applied in the reversed cyclic triaxial test during a cycle to the static undrained shear strength (Cu) and the initial effective stress (σ_0') respectively. It should be noted that under cyclic loading the same value of (Cu) was used to calculate τ /Cu applied in tension and compression.

The undrained shear strength was obtained from the monotonic tests carried out at a strain rate of 0.012% min. As tests of series A abd B were assymmetrically loaded, the parameters $(\tau /Cu)_{mean}$ $(\tau /\sigma_0')_{mean}$ are the mean values of τ /Cu and τ /σ_0' respectively. Semi-logarithmic plots of $(\tau/\sigma_0')_{mean}$ versus the number of cycles(N) required to cause 2 and 5% axial strain, are presented in Fig.1. It can be concluded that, with the exception of tests B.1 and B.2, the higher $(\tau/\sigma_0')_{mean}$, the smaller the number of cycles required to reach a specified double amplitude aial strain ϵ_{da} (i.e., 2 and 5%) were $\epsilon_{da}=|\epsilon_{Dmax}|+|\epsilon_{-Dmax}|$. (ϵ_{Dmax}) and (ϵ_{-Dmax}) are the axial strain associated with the maximum deviator stress in tension and compression, respectively.

It is also seen in Fig.1 that Kachachi's samples show higher resistance to cyclic loading than those of the author. This may well be due to frequency effect[14,15]. Plots of residual axial strain (ϵ_{Ap}) versus the number of cycles (N) for test C.3, taken as an example for tests series A,B and C, are seen in Fig.2. The observed tendency to favour a tensile mode of deformation is believed to be mainly due to the large difference in $(\tau/Cu)_{mean}$ to which the soil was subjected in compression and tension (Table 1). In fact, a comparison in terms of $(\tau/\sigma_0')_{mean}$ shows that the lower the ratio $(\tau/\sigma_0')_{mean}$, the higher the resistance to cyclic loading.

Despite the asymmetric loading (Table1), at the beginning of each test (1st cycle), the axial strains (ϵ_A) developed in compression were similar to those in tension. However, as the number of cycles increases, this equality disappears and ϵ_A becomes larger in tension than in compression. A much more symmetrical overall axial strain behaviour with only small tendency for greater (ϵ_A) in the tensile mode is observed in tests of series C, which were symmetrically loaded[15]. As observed for the double amplitude axial strain, the sequence of loading has no apparent effect on the develop-ment of (ϵ_A).

Figure 3 and 4 are Plots of secant modulus (E_s) against the number of cycles in compression and tension for Tests A.1 and B.4 (taken as representatives of the asymmetrically loaded tests) and test C.1 (taken as representative of tests of series C). It is seen that samples (Tests A.1, B.4 and C3) ended up with similar stiffness in compression and tension. It can also be seen, that during the first cycle, all samples of compression/tension tests were much stiffer under compressive loading than in tensile loading. However, the opposite behaviour is observed in tension/compression (Test C.4). It is believed that these different behaviours may be due to structural anisotropy resulting from the consolidation process and the direction of initial loading.

Axial strain and pore pressure behaviour: From examination of the data, the following observations were made:

A- In test A.1, ϵ_{max} and $+D_{max}$ occurred at the same time. However, with an increase in the number of cycles, ϵ_{max} occurred after D_{max}. ($+D_{max}$) and ($-D_{max}$) are the maximum value of the deviator stress in compression and tension respectively

B - In the remaining tests(i.e. B.4 and C.3),$|\pm \epsilon_{max}|$ occurred slightly after $+D_{max}$ and $-D_{max}$, respectively.

Bearing in mind the low frequency (0.00026 Hz) used in this investigation, the author believes that the latter behaviour may be due to creep effects. Creep is defined as the ability of the clay to continue deforming over a period of time under sustained load. The author would comment that these strains were in fact an indication of creep effect. In cyclic loading tests[16]. It is believed that at low cyclic stress ratios and particularly during the first cycle where only small strains develop, creep effects can be either non-existent or very small. The author also believes that as clay softening increases with the number of cycles, the effect of creep would become more apparent, as is the case in tests C.2, C.3 and C.4. However, it can also be deduced that, for some tests (for example A.3 and B.4) the amount of creep strain remained constant, while, for tests B.3 and C.1 the amount of creep strain has even been reduced. The author believes that the latter observations contradict the principal that creep effect increases with clay softening. These contradictions are believed to be mainly due to the difficulties involved in accurately measuring such very small amounts of strain[17].

As pore pressure generation is strain dependent, pore pressures are expected to be affected by creep (i.e., due to the stress paths, pore water pressure (U) will continue to increase in compression and decrease in tension after the maximum deviator stress was reached). It was observed that in the first cycle of series A and B, U_{mmax} and D_{max} occurred at the sane time. With increasing number of cycles, U_{mmax} occurred slightly after D_{max}, except for test A.3 which was the only test where both U_{mmax} and D_{max}, U_{min} and ($-D_{max}$) occurred at the same time. In tests of series C, U_{mmax} occurred before D_{max}. In tension, however, U_{min} in all cyclic tests (except test A.3) occurred slightly after ($-D_{max}$). U_{MC} is the mid-height pore pressure corrected by a factor of $-D/3$ in compression and $+D/3$ in tension. It was observed that the maximum value of U_{MC} is reached at approximately the middle of the cycle ($D=0$). The standard reversed triaxial test is conducted under the conditions of variable mean total stress, (i.e. while the axial load is varied, the cell pressure is maintained constant throughout a test). In order to investigate the effects of the change in the mean total stress on the behaviour of the Cowden Clay, each test was terminated by a cycle in which the cell pressure was varied either in phase with the axial load, as in test A1, in or out of phase, as in tests B.4 and C.3. For comparison purposes , mid-hieght pore presure (U_M), base pore pressure (U_B) and maximum cyclic shear stresses ($\pm \tau_{max}$) data from a previous cycle (where the cell pressure was constant) were also examined. The author would comment that it appears that cycling the cell pressure in or out of phase with the deviator stress would result in affecting the amplitude of pore pressure without resulting in any effect on the permanent pore pressure. The remaining differences in pore water pressures in the last cycle of tests B.4 may, in part, be due to some unwanted variation in mean total stress brought about by differences in amplitude between the deviator stress and the cell pressure, believed to be due to the following two main reasons:

Synchronisation: it was found to be extremely difficult to obtain a perfect synchronisation of the servo-hydraulic system used for the application of the axial load and the rotating mercury system to apply the variable cell pressure, as both devices were independently controlled.

Accuracy: although the maximum applied deviator stresses were constant, ($\pm \tau_{max}$) they were asymmetric because of the area change. This asymmetry gradually increased with increasing displacement, whereas the maximum and minimum amplitude of the cell pressure remained constant.

The author believes that the latter problems could be solved by the use of a servo-controlled water pressure system.

A comparison of the developed (ϵ_A) during the last two cycles, (with and without cell pressure variation, shows a small increase in (ϵ_A) during the last cycle. However, this increase in (ϵ_A) cannot be definitely attributed to the reduction in the mean total stress variation and could well be due to the softening induced by the extra cycle. Kvalastad *et al.*[18] performed two series of cyclic reversed triaxial tests, one with variable axial load and constant cell pressure and one with axial load and cell pressure varied out of phase in order to keep constant the octahedral normal stress (σ_{oct}) defined as ($\sigma_1 + 2\sigma_3$)/2. The samples were overconsolidated (OCR = 4) and tested by superimposing the cyclic shear stress upon a permanent compressive shear stress in order to avoid failure in tension. They reported that the effect of the octahedral normal stress on the overall cyclic behaviour of the

Drammen clay is insignificant. On the other hand, they observed that the effect of cyclic octahedral normal stress on the number of cycles to reach a certain permanent shear strain, (0.5%), is dependent on the shear stress amplitude. In fact, for a maximum shear stress, τ_{max} = 50- 62 kN/m^2, during cyclic loading, the clay becomes more resistant against cyclic loading. If the octahedral normal stress (σ_{oct}) is constant, the resistance increases with increasing ratio τ_P/τ_C. (τ_P and τ_C are the permanent and the cyclic shear stress respectively). It should be noted that this observation contradicts Kvalastad's earlier statement. In tests with τ_{max} = 69-75 kN/m^2, they observed the reverse behaviour, namely keeping σ_{oct} constant makes the clay less resistant to cyclic loading. This is also in contradiction with Kvalastad's earlier statement. Due to the inconclusive nature of the results reported in the present study, the author suggests that further investigation of the effects of the change in mean total stress during cyclic loading should be carried out before any definite conclusions are drawn.

Effective stress analysis: σ_{ax}' and σ_{lat}'are the axial and lateral effective stress derived from mid height pore pressure (U_M) From examination of the data, the following observations were made:

-(σ_{ax}')$_{max}$ and D_{max} occur almost at the same time, while (σ_{ax}')$_{min}$ occurs before (-D_{max}).

-In the first cycle of tests A.1 and B 4, (σ_{lat}')$_{min}$ occurred at the same time, while in the last cycle (σ'$_{lat}$)$_{min}$ occurred after D_{max}. For test C.3 (σ_{lat}') occurred before D_{max}. Plots of shear stress (σ_{ax}'-σ_{lat}')/2 versus mean effective stress (σ_{ax}' + σ_{lat}')/2 for a few cycles for the latter samples taken as examples are presented in Fig. 5 and Fig. 6. It is seen that the shape of the effective stress path varies with increasing (τ/Cu)$_{mean}$. Andersen *et al.*[9] (Fig. 7) reported that the most. significant problems they encountered were:

a) The existence of stress concentrations caused by end restraint due to friction between the clay and the end platens

b) Accurate measurement of rapid cyclic pore water pressure changes. The author believes that the latter two problems may be more pronounced for cyclic tests. Consequently, the author believes that the pore water pressures measured by Andersen et al may be erroneous and that both the effective static failure envelopes and the cyclic effective stress paths may have been affected.

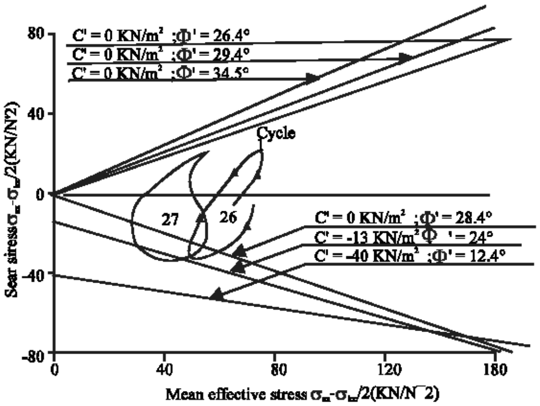


Fig. 5: Effective stress path for test A.1 (compression/ Tension)

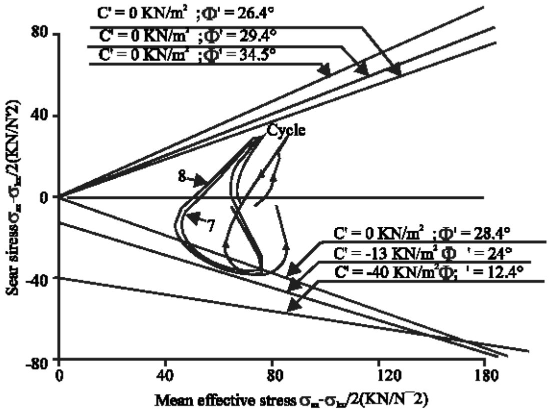


Fig. 6: Effective stress paths for test B.4 (compression/ Tension)

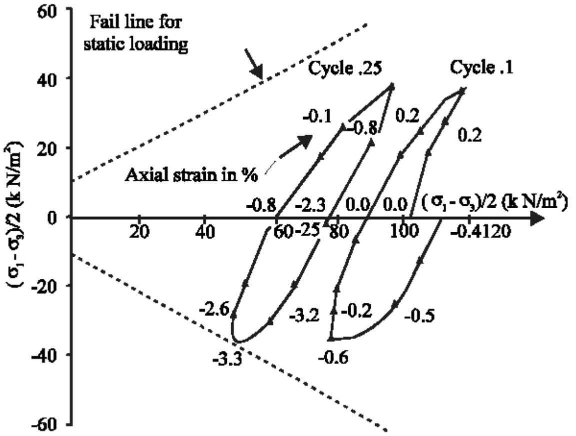
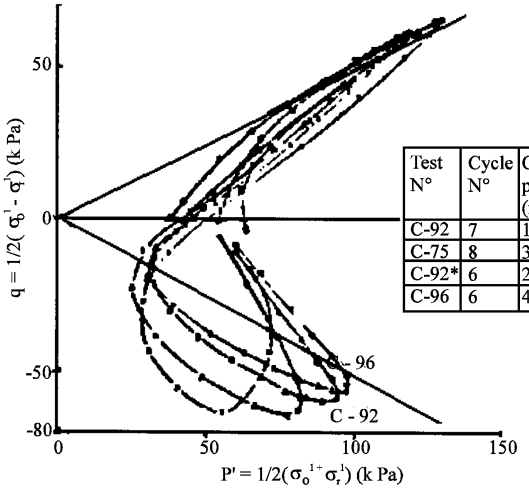


Fig. 7: Effective stress paths for typical reversed stress-controlled-triaxial test (Andersen *et al.* 1980)

The effective stress paths for the symmetrical tests of series C with τ/Cu)$_{mean}$ = ± 0.59, are similar to those obtained by Takahashi *et al.*[6] Fig. 8. It was also observed that, with the increasing number of cycles, the effective stress paths migrate towards the origin. In fact, the direction of migration of the stress path for compression/



Test N°	Cycle N°	Cycle period (min)
C-92	7	10
C-75	8	30
C-92*	6	240
C-96	6	480

Fig. 8: Effective stress paths for stress-controlled-triaxial tests with different stress ratios and frequencies (Takahashi *et al.*, 1980)

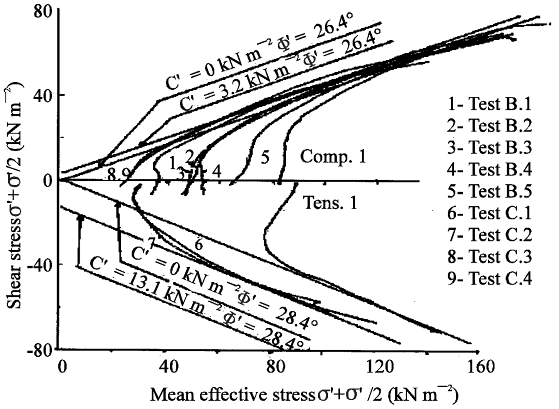


Fig. 9: Effective stress paths for post cyclic monotonic test

tension tests is initially away from the origin but subsequently reverses[6]. The author believes that this behaviour may be due to the tendency for volume increase associated with overconsolidated samples which would result in a decrease in pore pressure and an increase in the mean effective stress during the first cycle. However, as the number of cycles increases, the tendency for volume increase reduces and, due to reversed shearing, the pore water pressure level rises again resulting in a gradual decrease in the mean effective stress.

As a result of the sampling process, the samples used in the present investigation were also overconsolidated (Table 1). In tension/ compression test, it was observed that, with increasing number of cycles, the effective stress path migrates towards the origin from the start and that, particularly in tension, the effective stress paths travel beyond the effective failure envelopes inferred from the slowest monotonic tests (i.e., with a strain rate of 0.012%/min). It can be deduced that no effective stress path passed the effective failure envelope anticipated from the monotonic tests as long as the equivalent strain rate of the cyclic test was not higher than the strain rate of the monotonic tests from which the effective failure envelope was anticipated.

The equivalent strain rate was computed by dividing the axial strain developed during loading in tension, or in compression, in a cycle by the time taken to develop such axial strain ($Є_A$).

In order to investigate the effects of undrained cyclic loading on the undrained shear strength, all tests of series B and C were subjected to post-cyclic monotonic loading (Table 2). It was observed that only samples with a reduction in the initial effective stress of approximately 50% or more, as well as having suffered residual axial strains higher than 2%, show a decrease in the undrained shear strength. The reduction in the maximum deviator stress varies between 3% and 17%.

It is seen in Fig. 9 that both in compression and tension, the effective stress paths exceed the effective failure envelope from tests without cyclic loading. It appears from the effective failure envelopes for the post-cyclic tests that except for a small increase in C' from 0 to 3.2 and 13.1 kN/m^2 in compression and tension, respectively, Ø' has not been affected and that the level of the applied cyclic stresses was not high enough to affect Ø'. The author believes that even if no drainage has been permitted, the effective stress reduction during the undrained cyclic loading may have the same effect as if the effective stresses had been reduced by a real unloading of normal stresses. In other words, the cyclic loading may have caused an apparent over consolidation of the soil.

CONCLUSION

- Due to sample extraction, which results in a reduction in the initial effective stress, it is impossible to obtain. normally consolidated clay directly from the œdometer. Samples normally consolidated in the œdometer become lightly over consolidated in the triaxial cell
- After cyclic loading was terminated, both ends of the loading ram were disconnected to allow the transfer of the triaxial cell from the servo-hydraulic system to the conventional loading machine, where post-cyclic monotonic tests were carried out. This technique led to an increase in pore pressure. The author suggests that in future work all the tests carried out on a single sample should be performed on single machine to avoid any unwanted mechanical disturbance.

- The conventional loading machine and the servo hydraulic system used in this research were satisfactory. The accuracy of axial displacement measurement could be improved with an underwater L.V.D.T. set directly in contact with the specimen's top platen.
- The measurement of the cell pressure was successfully taken by means of a Bell and Howell diaphragm pressure transducer. However, the present device used for the application of the variable cell pressure was not sophisticated enough for perfect synchronisation of the cell pressure and deviator stress. It is felt that this can only be reached with the use of an integrated controlled pressure and deviatoric loading system.
- During cyclic loading it can be concluded that the higher the initial effective stress ratio (τ/σ_0') the smaller the number of cycles required to reach a specified double amplitude axial strain.
- Except for the first cycle, the stiffness measured in compression was similar to that measured in tension. During the first cycle of the compression/tension tests, the samples were much stiffer in compression than in tension. The opposite behaviour appears to occur under tension/compression loading. This behaviour may be due to structural anisotropy resulting from the consolidation process and the direction of initial loading.
- The initial migration of the effective stress path away from the origin also observed by Takashi *et al.* (1980)[6] is believed to be due to the tendency for volume increase associated with overconsolidated samples, which would result in a decrease in pore pressure and an increase in the mean effective stress during the first cycle. However, with an increasing number of cycles, the tendency for volume increase reduces and, due to reversed shearing, the pore water pressure level rises again, resulting in a gradual decrease in the mean effective stress.
- The fact that the effective stress paths for the cyclic tests travel beyond the effective failure envelopes inferred from slow monotonic tests appears to be related to differences in rate of loading.
- Accurate mid-height pore pressures were obtained.
- Mean excess pore pressure increases with the number of cycles.
- Good correlation of the double amplitude of the mid-height pore pressure with the theoretical change in mean total stress 2D/3 is observed.
- Cycling the cell pressure in or out of phase with the deviator stress appears to have no effect on the permanent pore pressure.
- Because of the limited amount of data available, the small increase in axial strain observed during the last cycle (with variable cell pressure), cannot definitely be attributed to the reduction in the mean total stress variation.
- Further investigation is needed of the effects of the variation of the mean total stress on the pore pressure behaviour and clay softening under monotonic (compression and tension) as well as under cyclic loading. This could be achieved if different series of monotonic and cyclic tests with the same initial effective stresses were carried out as follows:

    - Monotonic (compression/tension) tests with constant cell pressure
    - Monotonic compression/tension) tests with constant mean total stress
    - Cyclic (compression/tension and tension/ compression) tests with constant cell pressure
    - Cyclic (compression/tension and tension/ compression) tests with constant mean total stress.

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