Pore Pressure and Strength Behaviour of 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. 102mm high x102mm 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 slow reversed load controlled cyclic loading 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, height pore pressure, stress, creep, shear strength.

1 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, 2,3,4,5 and 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, 8, 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 1 cycle/hour has been used. Conventional reversed load-controlled triaxial tests are normally carried out by axial load at constant cell pressure. Cyclic loading of soil samples may result in softening so that the stress-strain properties are altered.

2 Experimental Apparatus and Material

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. The mid-height pore water pressure measurements were made by means of a miniature pressure transducer [12]. 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%; Plasticity index=25%; Clay fraction(D<0.002mm)=32%; Activity=78; CV of remoulded soil (σ'V = 480kN/m²) =1.5m²/yr. One final consolidation pressure of 600kN/m² was used for preparing remoulded samples of Cowden. 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. Undrained cyclic triaxial tests were performed on remoulded Cowden clay. The clay was normally consolidated in a cedometer to a pressure of 600 kN/m². Three sets (A,B,C) of load-controlled triaxial tests were carried out at a frequency of 0.00027Hz (Table 1.).

5.1 Axial strains

The author believes that, due to the difference in the initial effective stress (σo') 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/σo')mean. Plots of (τ/σo')mean versus the number of cycles(N) required to cause 2% and 5% are presented in figure 1. It can be concluded that, with the exception of tests B.1 and B.2, the higher (τ/σo')mean, the smaller the number of cycles required to reach a specified Cdu (i.e. 2% and 5%) Plots of residual axial strain (ЄAp) versus the number of cycles (N) for test C.3, taken as an example for tests series A,B and C, are seen in Figure 2. The tendency to favour a tensile mode of deformation observed is believed to be mainly due to the large difference in (τ/Cu)mean to which the soil was subjected in compression and tension (Table 1). In fact, a comparison in terms of (τ/σo')mean shows that the lower the ratio (τ/σo')mean, the higher the resistance to cyclic loading.

Despite the asymmetric loading at the beginning of each test (1st cycle), the axial strains developed in compression were similar to those in tension. However, as the number of cycles increases, this equality disappears and ЄA becomes larger in tension than in compression. A much more symmetrical overall axial strain behaviour with only all tendency for greater (ЄA) 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 development of (Єₐ).

Figures 3 and 4 are Plots of secant modulus (Eₛ) 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.

3 Discussion of the results
Plots of Ĉₐ, D, Uₘ, Uᵦ, Uₑ and Uₑₑ for tests A.1, B.4 and C3) are drawn for all tests. From examination of the data, the following observations were made:

Fig 1, τ / σₒ versus s number of cycles for all cyclic tests

A- In test A.1, which had in compression, Ĉₐₑ and +Dₘₐₓ occurred at the same time. However, with an increase in the number of cycles, Ĉₐₘₐₓ occurred after Dₘₐₓ.

B- In the remaining tests (i.e. B.4 and C3), │±Єₐₘₐₓ│ occurred slightly after +Dₘₐₓ and -Dₘₐₓ 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:

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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 will continue to increase in compression and decrease in tension after the maxim 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 same 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_Mmin and (-D_max) occurred at the same time. In tests of series C, U_Mmax occurred before D_max. In tension, however, U_Mmin in all cyclic tests (except test A.3) occurred slightly after (-D_max). It can also be 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, presented in or out of phase, as in tests B.4 and C.3. For comparison purposes U_M, U_B and maximum cyclic shear stresses (± τ_max) data from a previous cycle (where the cell pressure was constant) are 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:

1 -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.

2 -Accuracy: although the maximum applied deviator stresses were constant, \((\pm \tau_{\text{max}})\) 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 \((\varepsilon_A)\) during the last two cycles, (with and without cell pressure variation), shows, a small increase in \((\varepsilon_A)\) during the last cycle.

However, this increase in \((\varepsilon_A)\) 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. Kvalstad 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 \((\sigma_{\text{oct}})\) defined as \((\sigma_1 + 2\sigma_3)/2\). The samples were overconsolidated \((\text{OCR} = 4)\) 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 \(\tau_{\text{max}} = 50 - 62 \text{ kN/m}^2\) during cyclic loading, the clay becomes more resistant against cyclic loading if the octahedral normal stress \((\sigma_{\text{oct}})\) is constant, the resistance increasing with increasing ratio \(\tau_p \tau_c\) where \(\tau_p\) and \(\tau_c\) are the permanent and the cyclic shear stress respectively. It should be noted that this observation contradicts Kvalstad’s earlier statement. In tests with \(\tau_{\text{max}} = 69 - 75 \text{ kN/m}^2\), they observed the reverse behaviour, namely keeping \(\sigma_{\text{oct}}\) constant makes the clay less resistant to cyclic loading.

Plots of \(\sigma_{\text{ax'}}\) and \(\sigma_{\text{lat'}}\) derived from \(U_M\) measurements versus time for tests A.1 and B.4 were also drawn. From examination of the data, the following observations were made:

- \((\sigma_{\text{ax'}})_{\text{max}}\) and \(D_{\text{max}}\) occur almost at the same time, while \((\sigma_{\text{ax'}})_{\text{min}}\) occurs before \((-D_{\text{max}})\).
- In the first cycle of tests A.1 and B 4, \((\sigma_{\text{lat'}})_{\text{min}}\) occurred at the same time, while in the last cycle \((\sigma_{\text{lat'}})_{\text{min}}\) occurred after \(D_{\text{max}}\). For test C.3 \((\sigma_{\text{lat'}})\) occurred before \(D_{\text{max}}\). Plots of shear stress \((\sigma_{\text{ax'}} - \sigma_{\text{lat'}})/2\) versus mean effective stress \((\sigma_{\text{ax'}} + \sigma_{\text{lat'}})/2\) for a few cycles for the latter samples taken as examples are presented in Figures 5 and 6. It is seen that the shape of the effective stress path varies with increasing \((\tau/C_u)\text{mean}\). Andersen et al [9] (Figure 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. The effective stress paths for the symmetrical tests of series C with \((\tau/C_u)\text{mean} = \pm 0.59\), are similar to those obtained by Takahashi et al all [6] are shown in Figure 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/ 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. It 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 \((\varepsilon_A)\).

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. 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 Figure 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, \(\theta'\) has not been affected and that the level of the applied cyclic stresses was not high enough to affect \(\theta'\). 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.

4 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 \textit{oedometer}. Samples normally consolidated in the \textit{oedometer} become lightly over consolidated in the triaxial cell. 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. Contact with the specimen’s top platen, 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 ($\tau/\sigma_0'$) 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 [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.

- Accurate mid-height pore pressures were obtained.
References: