Indian Geotechnical Journal, 25 (4), 1995

Influence of Tube Penetration Distributions on Undrained Shear Characteristics of a Clay

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Introduction

In research, there have been basically two main approaches to investigate the effects of sampling clay soils. One approach has been to use a comparative study to investigate the effect on the soil parameters because of adopting different sampling techniques. The second approach, arisen as a result of greater understanding of the mechanisms associated with sample disturbance, is based on the idealizing the complete sampling process under controlled conditions in laboratory. The two idealized mechanisms considered in the sampling process are stress relief (Ladd and Lambe, 1963; Skempton and Sowa, 1963) and tube sampling strains (Baligh, 1985). The effects of tube sampling strains (i.e., tube penetration disturbances) on undrained shear behaviour of both reconstituted and natural clays have been reported by a number of researchers (Baligh et al., 1987; Lacasse and Berre 1988; Hajj 1990; Clayton et al., 1992; Wei et al., 1994). The reported results indicated significant changes in mean effective stress, stress-strain-strength, stiffness and pore pressure characteristics between the undisturbed samples and samples to which tube sampling strains were imposed. Numerical finite element analyses of sample disturbance due to penetration of tubes samplers of different cutting shoe designs also indicate that the levels of tube sampling strains depend markedly on the precise geometry of cutting shoe of samplers (Siddique, 1990). Experimental investigations to assess the effects of imposing varying degrees of tube sampling strains on subsequent undrained shear characteristics of clays would, therefore, lead to a better understanding of the importance of cutting shoe design of a sampler for sampling clays and for controlling tube sampling disturbances.

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This paper presents experimental results on the effects of imposing different levels of tube sampling strains on the undrained shear properties of a K_o– normally consolidated reconstituted soft plastic clay. The values of tube sampling strains were varied in an attempt to simulate the effects of realistic sampler geometries on the measured soil parameters.

Soil Used and Sample Preparation

The soil used in the study was brown plastic london clay. The London clay was obtained from Stag Hill site of the University of Surrey, England. The index properties of the clay are as follows:

Specific gravity	2.74
Liquid limit	69 %
Plasticity index	45 %
Clay fraction	54 %
Activity	0.83

Large blocks of clay were mixed with water in a soil mixer to prepare a homogeneous slurry which had a water content of approximately 1.5 times the liquid limit. The slurry was consolidated in a hydraulic consolidation cell of 1000 mm diameter by 490 mm deep. A pressure of 100 kN/m^2 was used during K_o– consolidation so as to obtain a soft sample at the end of consolidation. It took approximately 133 days for complete consolidation of the slurry. Large block samples (approximately 180 mm × 180 mm × 280 mm high) were cut by hand from the consolidated clay using wires. The blocks were placed in plastic bags which were de-aired and sealed. The samples were stored in a temperature controlled laboratory at 20 °C. Test samples were trimmed from the large block samples, using piano wire, a soil lathe and a split mould to a nominal dimensions of 102 mm diameter by 203 mm high. Water content and bulk density of the samples were respectively 45 ± 1 % and 1.76 ± 0.01 mg/m^3.

Testing Programme

The test programme consisted of performing two types of test. The stress and strain paths for which are shown schematically in Fig. 1 and the relevant stress and strain levels are summarized in Table 1. In samples LCD1 and LCD2, tube sampling strains imposed are approximately equivalent to those predicted numerically by Siddique (1990) at the centre line of NGI 54 mm diameter piston sampler (external diameter, D_e to thickness, t ratio = 45.6; area ratio, AR = 11.4 %; inside clearance ratio, ICR = 0.93 %) and SGI 50 mm diameter piston sampler (D_e/t = 12.2;

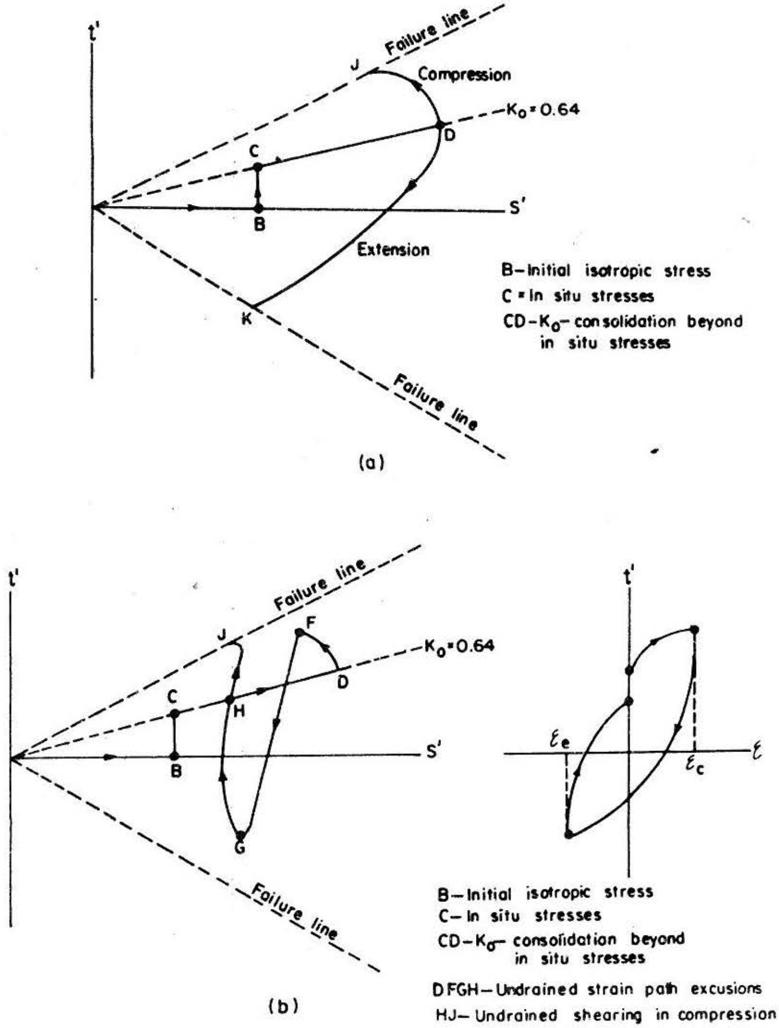

FIGURE 1 : Stress and Strain Paths Applied to London Clay Samples

AR = 44.0 %; ICR = 0.4 %) respectively. In sample LCD3, tube sampling strains applied are equivalent to those predicted by Baligh et al. (1987) at a centreline of a Simple Sampler ($D_e/t = 40$; ICR = 1 %). The test types are as follows :

(1) Firstly, conventional undrained triaxial compression and extension tests were carried out in order to determine the reference "undisturbed" behaviour of the clay. The stress paths are shown in Fig. 1(a). In these tests, samples were first bought back to their in-situ stresses (point C)

TABLE 1 : Details of the Tests of London Clay Samples

Sample	Stresses at Point D		Applied Tube Sampling Strains	
	σ_a' (kN/m^2)	σ_r' (kN/m^2)	ε_c (%)	ε_e (%)
LCU1	184	117	-	-
LCD1	183	116	0.25	-0.27
LCD2	190.4	122	0.5	-0.6
LCD3	185.6	116	1.0	-1.15

from their initial set up stresses (point B) by applying an undrained stress path at constant radial stress. The samples were then consolidated under K_o– conditions ($K_o = 0.64$) to vertical effective stress of 1.75 to 2 times the in-situ effective vertical stress, before being sheared in undrained triaxial compression (path DJ) and extension (path DK). Reconsolidation beyond in-situ stresses were done to eliminate the effects of sampling and sample preparation. A back pressure of 250 kN/m^2 was used during K_o– consolidation.

(2) In the second type of tests, K_o– consolidated samples were subjected to varying degrees of tube sampling strains (Baligh, 1985) by executing pre-specified undrained stress paths in compression and extension. Stress and strain paths are shown in Fig. 1(b). Tube sampling strains include maximum compressive strain (ε_c) during initial compression phase (path DF), maximum extension strain (ε_e) during extension phase (path FG) and minimum strain (0 %) during second compression phase (path GH). Finally, the samples were sheared in undrained compression (path HJ).

Apparatus, Instrumentation and Procedures

All samples were tested using 203 mm triaxial cell in a stepless compression machine which had facility of single drainage. Axial forces were measured using an internal load cell with a resolution of 1 N. Cell and back pressures were measured adjacent to the triaxial cell using pressure transducers with a resolution of 0.25 kN/m^2 each. A miniature pressure transducer (Hight, 1982) with a resolution of 0.25 kN/m^2 was used to measure mid-plane pore pressures. Local deformations were measured using Hall effect devices (Clayton et al., 1989). Two axial Hall effect devices having a gauge length of 70 mm each and one radial caliper were used. The resolutions of these axial strain and radial strain devices were 1 μm and 0.5 μm respectively. Axial strains were also measured using a displacement transducer with a resolution of 6 μm. All instrumentation was monitored using a microcomputer.

An automated stress path system (Khatrush, 1987; Siddique, 1990) was used to control the stresses imposed on "undisturbed" and "disturbed" samples. The system was controlled by a microcomputer. Two automated pressure controllers controlled the air pressure applied to the cell and back pressure air/fluid Bellofram rolling diaphragm. A third automated pressure controller regulated the air supply to a double acting Bellofram rolling diaphragm air actuator that was connected to the internal load cell. Air pressure increments of 0.1 kN/m^2 was attainable which corresponds to about 0.07 kN/m^2 for the axial pressure on the sample. This set up allowed any stress path to be followed. All stress paths were controlled and logged by the microcomputer. During performing the drained stress paths for all samples [path CD, Fig. 1(a) and (b)], the vertical effective stress was increased at approximately 0.7 $kN/m^2/hr$. Tube sampling strains during the strain path excursions [path DFGH, Fig. 1(b)] were imposed on the samples by allowing the samples to follow pre-assigned stress paths in undrained compression and extension. The rate of increase of axial stress during path DF was 5 $kN/m^2/hr$ while axial stress was decreased and increased during paths FG and GH respectively (Fig. 1b) at rate of 50 $kN/m^2/hr$. During undrained shearing to failure (path HJ) deviator stress was increased at a rate of 10 $kN/m^2/hr$ with constant cell pressure.

Results and Discussion

Stress Paths

Normalized effective stress paths in $s'-t'$ [$s' = (\sigma'_a + \sigma'_r)/2$, $t' = (\sigma'_a - \sigma'_r)/2$] space for two tests which simulated the application of tube sampling strains are presented in Figs. 2(a) and (b). The stress paths of the "undisturbed" samples, sheared both in compression and extension, are also shown in Fig. 2 as dashed lines. The stress paths in Figs. 2(a) and (b) show the following features :

(i) During the first compression phase, s' decrease with the increase in t'.

(ii) During the extension phase, s' reduces with the decrease in t'. The effective stress path did not touch the yield surface in extension.

(iii) During the second compression phase, s' increases slightly with the increase in t'.

(iv) During undrained shearing (i.e., after the application of tube sampling strains), s' remains almost constant with the increase in t'.

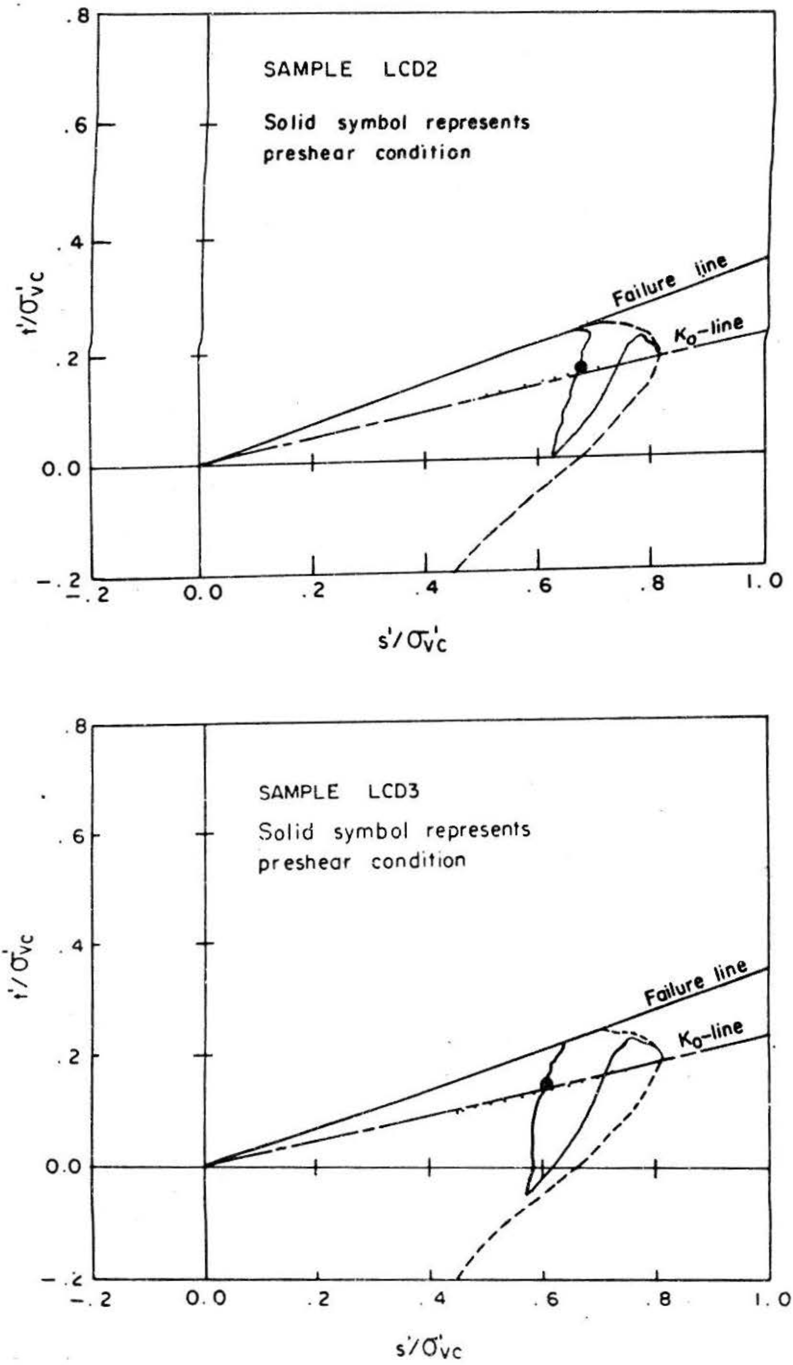

FIGURE 2 : Normalised Effective Stress Paths in s' – t' Space
a) Sample LCD2 b) Sample LCD3

TABLE 2 : Mean Effective Stress of the "Disturbed" Samples

Sample	p_i' (kN/m²)	p_o' (kN/m²)	ε_T (%)	Reduction in p'
LCD1	138.0	123.6	1.04	10%
LCD2	144.8	119.6	2.2	17%
LCD3	139.2	103.6	4.3	26%

Comparing the stress paths during undrained shearing in compression it can be seen that the nature of the stress paths of the "disturbed" samples LCD2 and LCD3 are markedly different from that of the "undisturbed" sample LCU1. For sample LCU1, s' reduced with the increase in t'. However, for samples LCD2 and LCD3, s' remained almost constant with the increase in t'. The "disturbed" samples LCD2 and LCD3 produced stress paths similar to those of overconsolidated clays. In case of reconstituted Boston Blue clay (LL = 42; PI = 20), Baligh et al. (1987) also found appreciably different effective stress paths for the undisturbed sample and the sample to which tube sampling strains have been imposed.

Changes in mean effective stress

One of the most significant effects due to application of tube sampling strains is the reduction in mean effective stress, $p'\left[=\left(\sigma_a' + 2\sigma_r'\right)/3\right]$. The reduction in mean effective stress, expressed as a percentage of initial mean effective stress before the application of disturbances, is presented in Table 2. In Table 2, ε_T refers to total strain applied during imposing tube sampling strains which being equal to the summation of axial strains subjected to a sample during the initial compression phase, extension phase and second re-compression phase. It can be seen from Table 2 that, depending in the value of ε_T, mean effective stress decreased between 10 to 26 %. Baligh et al. (1987) and Clayton et al. (1992) found a reduction in p' of 59 % and 43 % respectively in reconstituted Boston Blue clay (LL = 42 %, PI = 20 %) and natural Bothkennar clay (LL = 76 %, PI = 42 %). In these tests, a strain path excursions of amplitude ±1 % (i.e., ε_T = 4 %) were applied to samples which were equivalent to those obtained along the centreline of a Simple sampler (Baligh et al., 1987) with D_e/t of 40 and ICR of about 1 %. For approximately equivalent strain path excursions in reconstituted soft London clay (LL = 69, PI = 45) used in this study, the value of p' reduced by 26 %.

Undrained Stress-Strain-Strength Properties

Figure 3 shows typical normalized deviator stress (q) versus axial strain

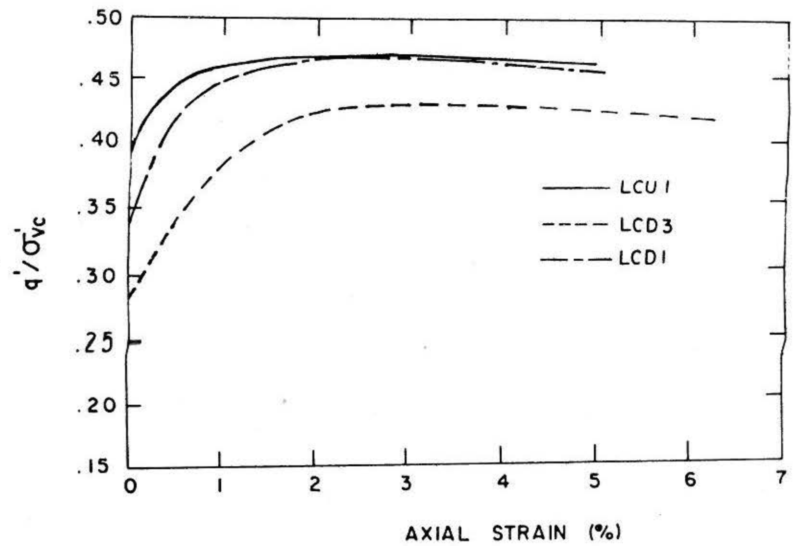

FIGURE 3 : Normalised Deviator Stress versus Axial Strain Plots

(ε_a) plots during undrained shearing after the application of tube sampling strains for samples LCU1, LCD1 and LCD3. The following important features can be seen from Fig. 3 :

(i) The peak undrained shear strength (Cu) of the "disturbed" samples (LCD1 and LCD3) is mobilised at axial strains considerably larger than that for "undisturbed" sample (LCU1).

(ii) For all the samples, the strength mobilised at larger strains is slightly less than that mobilised at peak. Therefore, the samples did not show any undrained brittleness behaviour when sheared in compression.

(iii) The strain – strain relationships are non-linear.

A comparison of the strength parameters (i.e., effective angle of internal friction, ϕ' and c_u) and axial strain at undrained peak strength, ε_p is presented in Table 3. It can be seen from Table 3 that, compared with the "undisturbed" sample LCU1, ϕ' increased only slightly (1 - 3 %) while c_u reduced slightly (2 - 6 %) due to application of tube sampling strains. A small increase (1 - 4 %) in c_u, however, for sample LCD2 has been found. Baligh et al. (1987) reported a 21 % reduction in undrained strength ratio (c_u/σ_{vc}') for Boston Blue clay while Lacasse and Berre (1988) found about the same c_u in triaxial compression for "disturbed" and "undisturbed" samples of normally consolidated and overconsolidated (OCR = 2.5) plastic natural Drammen clay (PI = 27). In these tests, strain path excursions of amplitude ± 1 % were applied to samples. Clayton et al. (1992) reported a

TABLE 3 : Comparison of Strength Parameters and ε_p

Sample	ϕ' (in degrees)	c_u (kN/m^2)	ε_p (%)
LCU1	19.6	43.1	1.5
LCD1	20.0	42.4	1.9
LCD2	20.2	43.7	3.3
LCD3	19.8	40.6	3.4

reduction in c_u of ½ to 10 % in natural Bothkennar clay samples (PI = 42 to 54) for tube sampling strains of amplitude between ± 0.5 % and ± 2.0 %. Table 3 shows that, compared with "undisturbed" sample LCU1 the values of ε_p increased significantly because of imposing tube sampling strains. In sample LCD1, ε_p increased by about 27 % while in sample LCD3 ε_p increased by as much as 127 %. It is also apparent that increase in ε_p increases with increasing levels of tube sampling strains. Baligh et al. (1987) also found a quite appreciable increase (about 27 times) in ε_p due to tube penetration disturbances in Boston Blue clay.

Undrained Stiffness Properties

The initial tangent modulus, E_i secant modulus at half the peak deviatoric stress, E_{50}, undrained shear modulus, G_u were determined for the "undisturbed" sample (LCUI) and all the "disturbed" samples. A comparison of these parameters is presented in Table 4. It can be seen from Table 4 that tube sampling strains caused considerable reduction in E_i, E_{50} and G_u. For *the sample LCDI which has been subjected* to least disturbances, E_i, E_{50}

TABLE 4 : Comparison of Stiffness Parameters (E_i, E_{50} and G_u)

Sample	E_i (kN/m^2)	E_{50} (kN/m^2)	E_u (kN/m^2)
LCU1	9815	5998	3999
LCD1	4968	4350	1579
LCD2	3708	3271	1046
LCD3	2241	2101	780

and G_u are reduced by 49 %, 27 % and 61 % respectively. For a strain path excursions of amplitude ± 1 %, Baligh et al. (1987) reported a decrease in undrained modulus ratio (E_{50}/σ_{vc}') of as much as 95 %, compared with a reduction of 65 % found for London clay. Lacasse and Berre (1988) also reported significant reduction in initial moduli for normally consolidated and overconsolidated samples of Drammen clay due to application of an equivalent tube sampling strains. For Bothkennar clay, Clayton et al. (1992) reported a reduction in normalized secant stiffness (at 0.1 % axial strain) of 30 to 61 %, when the amplitude of the strain cycle was increased above ± 0.5 %. However, an increase in stiffness of 32 % was found following a strain cycle of + 0.5 % which has been attributed to reduction in water content during re-consolidation more than compensating any damage to the structure due to disturbances during the application of tube sampling strains.

Changes in the small strain characteristics due to application of tube sampling strains were also assessed. The changes in small stress-strain properties have been evaluated in terms of stiffness index $\left(E_u\right)_{0.01\%}/p_o'$ and the linearity parameter $L\left[=\left(E_u\right)_{0.1\%}/\left(E_u\right)_{0.01\%}\right]$ as suggested by Jardine (1985). $\left(E_u\right)_{0.01\%}$ and $\left(E_u\right)_{0.1\%}$ refer to secant stiffness at 0.01 % and 0.1 % axial strain respectively while p_o' is the mean effective stress prior to undrained shear after the application of tube sampling strains. Stiffness index is a measure of small strain zone and the second index L is a measure of non-linearity in stress-strain behaviour (Jardine, 1985). The greater the value of $\left(E_u\right)_{0.01\%}/p_o'$, the larger is the size of the small strain region, and higher the value of L, the greater is the degree of linearity in the stress-strain behaviour. A value of L = 1 indicates a linear stress-strain behaviour. A comparison of secant stiffness at small axial strain levels, stiffness indices and linearity parameters is shown in Table 5. Table 5 shows that secant stuffiness at various strain levels and stiffness indices of the "disturbed" samples reduced appreciably while no significant change in non-linearity has been observed. Compared with sample LCUI, the parameters

TABLE 5 : Comparison of Small Stiffness Properties

Sample	E_u (kN/m^2)			$\left(E_u\right)_{0.01\%}/p_o'$	L
	at 0.01%	at 0.05%	at 0.1%		
LCU1	15011	9228	7143	108	0.476
LCD1	8225	4812	4406	67	0.476
LCD2	6683	3337	3002	56	0.536
LCD3	4853	1970	1819	47	0.375

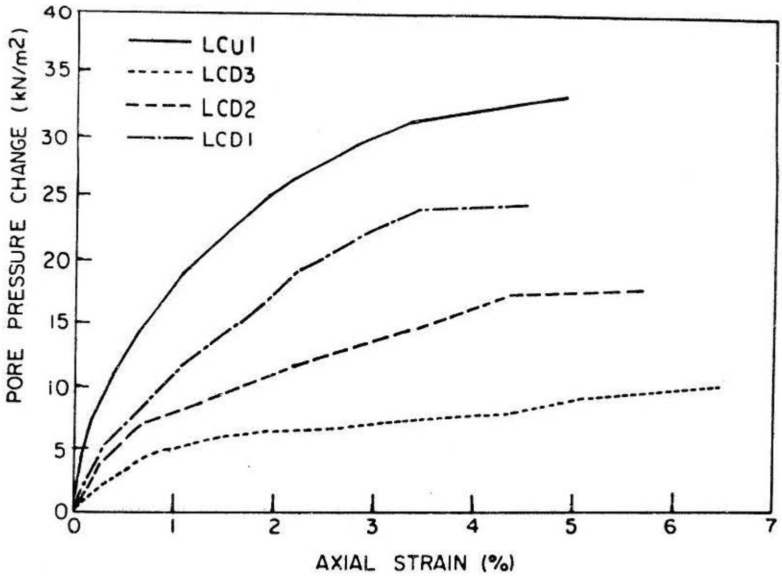

FIGURE 4 : Comparision of Pore Pressure Changes Between the "Undisturbed" and "Disturbed" Samples of London Clay

$(E_u)_{0.01\%}$, $(E_u)_{0.05\%}$, $(E_u)_{0.1\%}$ and stiffness index, $(E_u)_{0.01\%}/p'_o$ have been reduced by 45 to 68 %, 48 to 79 %, 38 to 75 % and 38 to 56 % respectively.

Pore Pressure Characteristics

A comparison of pore pressure changes (Δu) during undrained shearing of "undisturbed" and "disturbed" samples is shown in Fig. 4. It can be seen that Δu reduced appreciably because of applied tube sampling strains. Skempton's pore pressure parameter A at peak strength A_p for all the samples have been determined. The values of A_p for the samples LCU1, LCD1, LCD2, and LCD3 are respectively 1.25, 0.74, 0.55 and 0.27. It, therefore, appears that application of tube sampling strains reduced the value of A_p considerably and that the reduction in the values of A_p increases with increasing levels of tube sampling strains. Compared with the "undisturbed" sample LCU1, the values of A_p decreased by 41 %, 56 % and 78 % for the samples LCD1, LCD2 and LCD3 respectively.

Conclusions

Triaxial stress path tests have been carried out to investigate the effects of tube penetration disturbances on undrained shear properties of reconstituted K_o – normally consolidated London clay. Tube sampling strain applied to samples have led to large reductions (10 to 26 %) in mean effective stress. The strength parameters, Cu and ϕ', were not, however, changed significantly. Initial tangent modulus, E_i, secant modulus at half the peak deviatoric stress, E_{50}, undrained shear modulus, G_U were all reduced quite considerably. For strain path excursions of amplitude ± 1 %, E_i, E_{50} and G_U have been reduced by 77 %, 65 % and 80 % respectively. Considerable reductions in secant stiffness at small strain levels have been found. Marked changes in pore pressure responses have been observed because of imposed tube sampling strains. Skempton's pore pressure parameter A at peak strength was 41 to 78 % less for the "disturbed" samples than for the "undisturbed" sample. Tube penetration disturbances have also caused quite an appreciable increase (27 to 127 %) in axial strain at peak strength.

Test results of reconstituted normally consolidated London clay, therefore, clearly indicate that tube penetration disturbances have profound effects on the mechanical properties of a clay. The higher the tube sampling strains, the greater is the changes in the undrained soil parameters. The relative effects indicate that it is virtually impossible to obtain good quality undisturbed samples of normally consolidated soft clays using thin- walled tube samplers. Experimental findings, therefore, indicate the need for reevaluation and possibly modifications of current soil sampling methods for soft clays.

Notation

A	=	Skempton's pore pressure parameter
AR	=	area ratio of sampler
A_P	=	Skempton's pore pressure parameter A at peak strength
D_e	=	external diameter of sampler
c_u	=	peak undrained secant stiffness
E_u	=	undrained secant stiffness
E_i	=	initial tangent modulus
E_{50}	=	secant modulus at half the maximum deviatoric stress
G_u	=	undrained shear modulus
ICR	=	inside clearance ratio of sampler
L	=	linearity parameter
LL	=	liquid limit
PL	=	plastic limit

PI	=	plasticity index
p'	=	mean effective stress $(\sigma_a' + 2\sigma_r')/3$
p_i'	=	initial mean effective stress at the end of K_o – consolidation
p_o'	=	mean effective stress prior to undrained shearing
q	=	deviatoric stress $(\sigma_a' - \sigma_r')$
s'	=	$(\sigma_a' + \sigma_r')/2$
t	=	thickness of sampler
t'	=	$(\sigma_a' - \sigma_r')/2$
u	=	pore pressure
Δu	=	change in pore pressure
ε_a	=	axial strain
ε_c	=	maximum axial strain in compression
ε_e	=	maximum axial strain in extension
ε_p	=	axial strain at peak strength
ε_T	=	total axial strain applied during strain path test
σ_a'	=	axial effective stress
σ_r'	=	radial effective stress
σ_{vc}'	=	vertical effective stress at the end of K_o – consolidation
ϕ'	=	effective angle of internal friction

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