EFFECTS OF SAMPLING DISTURBANCE ON MECHANICAL PROPERTIES OF RECONSTITUTED NORMALLY CONSOLIDATED AND OVERCONSOLIDATED DHAKA CLAY

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A Thesis

by

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DECLARATION

I hereby declare that the research work reported in this thesis has been performed by me and that this work has not been submitted elsewhere for any the purpose, except for publications.

Part of the results of the research have been accepted for publication in the proceedings of the "YEAR 2000 GEOTECHNICS" Geotechnical Engineering Conference to be held during 27 - 30 November, 2000 at AIT, Bangkok, Thailand.

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ABSTRACT

The present study has been carried out to investigate the effects of sampling disturbance on mechanical behaviour of reconstituted normally consolidated and overconsolidated Dhaka clay (OCR values of 2, 5, and 10). Disturbed Dhaka clay samples were collected from Rupnagar Housing Project, Mirpur-11, Dhaka. The clays were low to medium plasticity (LL = 47, PI= 26). Reconstituted normally consolidated samples of Dhaka clay were prepared in the laboratory by K_0-consolidation of slurry in a large cylindrical consolidation cell using a consolidation pressure of 150 kN/m^2 while overconsolidated samples having OCR values of 2, 5 and 10 were prepared by reducing the maximum pressure of 150 kN/m^2 to 75 kN/m^2, 30 kN/m^2 and 15 kN/m^2 respectively. "In situ" samples were prepared (by consolidating 38 mm diameter by 76 mm high specimens under K_0-conditions in the triaxial cell) to its "in situ" stress state. "Tube" samples of various OCR values were prepared from the large diameter consolidated sample by inserting samplers of different area ratio, external diameter to thickness ratio (D_e/t) and outside cutting edge angle (OCA). The area ratio, D_e/t ratio and OCA of the samplers varied from 16.4% to 73.1%, 27.3 to 8.3 and 5° to 20° respectively. Normally consolidated and overconsolidated "perfect" samples were prepared from respective "in situ" samples by undrained release of the total stress in the triaxial cell. Undrained triaxial compression tests were carried out on "in situ", "tube" and "perfect" samples. "Tube" and "perfect" samples having OCR values of 2 and 10 were also reconsolidated isotropically and anisotropically under K_0-condition using Bjerrum (CK_0U-1.0σ'_{vc}) and SHANSEP (-1.5σ'_{vc} and -2.5σ'_{vc}) procedures.

Disturbance due to perfect and tube sampling have significant influence on the mechanical properties of normally consolidated and overconsolidated Dhaka clay. Disturbance due to perfect sampling led to reduction in the values of s_u and A_p while E_i, E_{50} and ε_p increased caused due to total stress relief. Because of perfect sampling undrained strength (s_u) reduced up to 8.2% while, axial strain at peak deviator stress (ε_p) increased up to 20.9% for samples of OCR value of 10. Due to perfect sampling pore pressure parameter at peak deviator stress (A_p) reduced up to 90% while, initial tangent modulus (E_i) and secant stiffness at peak half deviator stress (E_{50}) increased up to 14.0% and 19% respectively for normally consolidated sample. Due to total stress relief for perfect sampling disturbance, the reduction in s_u increases with increase in OCR while, the increase in E_i, E_{50} reduce with increase in OCR.

The initial effective stress (σ'_i) of "tube" samples reduced considerably because of disturbance caused by penetration of tubes. Compared with " in situ" samples, values of s_u, E_i, E_{50} and A_p of the "tube" samples reduced while ε_p increased. Changes in measured soil parameters between the "in situ" and "tube" samples have been found to depend significantly on the sampler characteristics (area ratio, D_e/t ratio and OCA) used for retrieving the "tube" samples. The values of σ'_i, S_u, and E_i were reduced up to 26.2%, 43% and 62% respectively for normally consolidated sample due to increase in area ratio from 16.4% to 73.1% (or reduction in D_e/t ratio from 27.3 to 8.3). The respective reductions for normally consolidated sample due to increase in OCA from 4° to 15° are 21.9%, 38% and 60%. Values of ε_p for OCR values of 1 and 5, increased up to 57.7% and 52.6% due to increase in area ratio and OCA respectively. A quantitative increase in the degree of disturbance (D_d) has been obtained due to increase in area ratio and OCA. The results indicates that compared with normally consolidated reconstituted Dhaka Clay, tube sampling causes relatively little degree of disturbance in overconsolidated reconstituted Dhaka Clay. The reduction in initial effective stress due to tube sampling reduces with increase in OCR. The increase in value of ε_p due tube sampling reduces with increasing OCR. For tube sampling disturbance, trend of small decrease in the reduction of s_u / σ'_{vc}, E_i / σ'_{vc} and E_{50} / σ'_{vc} obtain with increasing OCR. However, significant increase in reduction of A_p with increasing OCR has been observed.

It appeared that for good quality sampling, a sampler ought to have a well combination of area ratio and OCA. In order to reduce disturbance due to sampling in soft Dhaka clay, area ratio and OCA of sampler should be kept practically as low as possible. A correction curve has been provided from the plot of strength ratio versus overconsolidation ratio for samples of Dhaka clay. This correction curve can be used to find the perfectly undisturbed strength of the tube samples retrieved of Dhaka clay for use in analyses and designs.

Isotropic reconsolidation (CIU-1.0σ'_{vc}) has the effect of gross overestimation of "in situ" strength, ε_p and E_i for the "tube" and "perfect" samples. It has been found that compared with SHANSEP procedures reconsolidation using Bjerrum procedure (CK_OU-1.0σ'_{vc}) for both "tube" and "perfect" samples of overconsolidated Dhaka clay, produced the best overall estimate of the "in situ" properties in terms of undrained strength, stiffness, strain and pore pressure response.

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NOTATIONS

A	Skempton's pore pressure
A_p	Skempton's pore pressure parameters at peak deviator stress
A_u	Skempton's pore pressure parameter for the undrained release of shear stress
B	Skempton's pore pressure parameter
D_d	Degree of disturbance
D_i	Internal diameter of the cutting edge of the sampler
D_s	Inside diameter of the sampler tube
D_w, D_e, B	External diameter of the sampler
E_i	Initial tangent modulus
E_{50}	Secant stiffness at half of peak deviator stress
K_0	Coefficient of earth pressure at rest
P'_c	Maximum consolidation effective pressure
P'_0	Initial mean effective stress
S_t	Sensitivity
s_u, c_u	Undrained shear strength
s_u/σ'_{vc}	Normalised Undrained shear strength
t	Thickness of the sampler
s'	$(\sigma_a' + \sigma_r')/2$
t'	$(\sigma_a' - \sigma_r')/2$
Δu	Pore pressure change
ϵ_a	Axial strain
ϵ_p	Axial strain at peak deviator stress
ϵ_v	Volumetric strain
ϵ_{max}	Maximum axial strain
σ'_a and σ'_r	Vertical and Horizontal effective stress
σ_i', σ_c'	Initial or residual effective stress
σ'_{ps}, σ'_{cm}	Isotropic effective stress of a "perfect" sample
σ'_{vc}	Vertical effective stress after K_0-consolidation

GLOSSARY

AR	area ratio
axial strain history	cycle of strains at centre-line of tube sample samplers as predicted by Baligh (1985) and Siddique (1990)
destructuring	process of removing the structure of natural clay soils
deviator stress relief	release of deviator stress of zero, but maintaining the isotropic total stress
CL	centre line
CSR .	cutting shoe radius
CIU	isotropically consolidated undrained test
CK_0U	K_0-consolidated undrained test
ICR	inside clearance ratio
ICA	inside cutting edge angle
ideal sampling	tube sampling strain path excursions together with perfect sampling (Baligh, Azzouz and Chin, 1987)
ideal tube sampling	experimental simulation of tube sampling
NC	normally consolidated
NMC	natural moisture content
LL	liquid limit
OC	overconsolidated
OCA	outside cutting edge angle
OCR	overconsolidation ratio
Perfect sampling	release of deviator stress to zero (Skempton and Sowa, 1963)
PI	plasticity index
PL	plastic limit
Reconstitued	term for a clay soil which has been remoulded at a water content of between one and one and half times the liquid, without air or oven drying and then consolidated under one-dimensional conditions

remoulded	term for a clay which has been remoulded without changing its moisture content
SHANSEP	stress history and normalized soil engineering properties (Ladd and Foott, 1974)
Simple sampler	the profile of a tube sampler which is produced by superimposing a uniform flow with a single ring source (Baligh, 1985)
Strain cycle amplitude	amplitude in %, of the strain path excursion
strain path excursions	cycle of strains imposed on specimens during ideal tube sampling based on axial strain history
strain path method	predictions of axial strain history based on the simulation of the flow of soil around a tube sampler (Baligh, 1985)
strain path	a state path where deformation control is used
stress path	a state path where stress control is used
total stress relief	release of total stresses to zero
USCS	unified soil classification system
UU	unconsolidated undrained test

CHAPTER 1

INTRODUCTION

1.1 GENERAL

For the design of the foundations of structures, the geotechnical engineers require a knowledge of the engineering properties of the foundation soils which are estimated either form results of in situ or laboratory testing. Both procedures involve penetration of samplers or other rigid devices in the ground that inevitably cause disturbance to the soil. In situ testing suffers from a number of disadvantages and as such it is not an entirely satisfactory procedure. These disadvantages include poorly defined boundary conditions in terms of stresses and deformations and uncertain drainage conditions of the soil under investigation (Jamiolkowski et al., 1985). Laboratory testing is carried out on soil sample having previously retrieved it from the ground using some form of sampling procedure. In the laboratory the stresses, deformations and boundary conditions can be readily and precisely controlled and observed (Jamiolkowski et al., 1985). Sampling approach is therefore widely adopted.

Broadly, the soil sampling procedure in clays consists of a number of different stages. Initially a borehole is excavated or drilled to the desired sampling depth. The soil is then sampled using a sampler. The soil sample is then brought to the surface and transported to the laboratory, where it is tested. The inherent problem with the sampling process is that it disturbs the soil sample. This disturbance can be significant, such that the behaviour of the soil in the laboratory differs greatly from its behaviour in situ. The effect of sample disturbance on a clay soil depends on many factors including the type of clay, the method of sampling, sealing, storage, specimen preparation and testing procedure. Geotechnical engineers predict the behaviour of the in situ soil based on soil parameters obtained from laboratory investigation of sampled soil. Soil disturbance is often regarded as a significant problem because it is thought to prevent acquisition of realistic soil parameters. It is therefore extremely important that geotechnical engineers have a sound understanding of the extent, both qualitatively and quantitatively, to which the parameters being used have been affected by the sampling process.

During sampling, a clay soil is disturbed in two major ways.

(i) Firstly, mechanical disturbance caused when sampler is pushed into the soil. This disturbance is termed as tube penetration disturbance.

(ii) Secondly, disturbance caused by the release of the total in situ stress after the soil has been sampled. Such a disturbance is called "perfect" sampling disturbance.

Soil disturbance can be minimized by careful control of the whole sampling process and by using properly designed sample tubes. In clays, one of the most important contributory factors to sample disturbance is the precise design of the cutting shoe of the sampler being used for sampling. The design of a sampler is one of the most important aspects that should be considered for good quality sampling. The degree of disturbance varies considerably depending upon the dimensions of the sampler and the precise geometry of the cutting shoe of the sampler (Hvorslev, 1949; Kallstenius, 1958; Andresen, 1981; La Rochelle et al., 1981; Baligh et al., 1987; Tanaka et al., 1996; Siddique, 1990; Siddique and Sarker;1996, Siddique and Clayton, 1995; Clayton et al., 1998, Clayton and Siddique, 1999; Siddique and Farooq, 1998).

Locally made Shelby tubes are usually used for undisturbed sampling in most of the soil investigation programme in Bangladesh. These sample tubes normally do not meet the proper design requirements of the sampling tube and cutting shoe for good quality sampling. As such, the samples collected using these tubes, do not represent the in situ state and are often of poor quality. As a result, laboratory tests conducted on these samples do not provide realistic soil parameters to be used for geotechnical analyses and designs. In fact, a sampling tube should be designed in such a way that it retrieves samples subjected to minimum disturbance.

A few research works were carried out to investigate the effects of tube sampling and perfect sampling on the undrained shear properties of regional clays of Bngladesh (Sarker, 1994; Farooq, 1995; Siddique and Farooq, 1996; Siddique and Sarker 1997; Bashar et, al.1997). Sarker (1994) investigated the effects of tube and "perfect" sampling disturbance on the undrained shear behaviour of normally consolidated reconstituted soft Dhaka clay while Farooq (1995) invetigated the influence of tube and "perfect" sampling on the undrained shear behaviour of three normally consolidated reconstituted soft coastal soils.

Investigations on the effect of the design parameters of tube samplers (e.g., area ratio, external diameter to thickness ratio and outside cutting edge of sampler) on the laboratory measured soil parameters have also been conducted for normally consolidated reconstituted soft Dhaka clay and soft coastal soils (Sarker, 1994; Farooq, 1995; Siddique and Sarker, 1996; Siddique and Farooq, 1998).

In fact, intact Dhaka clays are usually slightly overconsolidated at shallow depths. Although a number of research works have been carried out to investigate the generalized behaviour of reconstituted normally consolidated and overconsolidated Dhaka clay (e.g., Ameen, 1985; Kamauddin, 1990; Siddique and Safiullah, 1995; Shariful, 1999), no research has been carried out to investigate of sampling effects on the mechanical properties of overconsolidated Dhaka clay. The present investigation has, therefore, been aimed to investigate the effects of tube penetration disturbance and perfect sampling disturbance on the mechanical properties of reconstituted overconsolidated clay. Attempt has been made to examine the effect of the design parameters of tube sampler, namely area ratio, external diameter to thickness ratio and outside cutting edge angle, on the measured soil parameters of reconstituted overconsolidated Dhaka clay. The present research also aims to assess the influence of different reconsolidation procedures in order to minimize the possible effects of both tube sampling and perfect sampling disturbance in the reconstituted overconsolidated Dhaka clay.

1.2 OBJECTIVES OF THE PRESENT RESEARCH

The principal objectives of the research are as follows:

(i) To carry out K_0-consolidated undrained (CK_0U) triaxial compression tests on overconsolidated (OCR values of 1, 2, 5 and 10) "in situ" samples to determine the reference undisturbed behaviour of the overconsolidated Dhaka clay.

(ii) To carry out unconsolidated undrained triaxial compression tests on overconsolidated (OCR values of 1, 2, 5 and 10) "tube" samples of reconstituted Dhaka clay in order to investigate the effects of tube sampling disturbance on mechanical properties, e.g., strength, deformation, stiffness and pore pressure of overconsolidated Dhaka clay.

(iii) To investigate the effects "Perfect" sampling on stress-strain-strength, stiffness and pore pressure characteristics of normally consolidated and overconsolidated (OCR values of 2, 5 and 10) Dhaka clay.

(iv) To investigate the influence of the design parameters of tube sampler (e.g., area ratio, external diameter to thickness ratio and outside cutting edge angle) on the undrained soil parameters of reconstituted overconsolidated (OCR = 1, 2, 5 and 10) Dhaka clay.

(v) To carry out triaxial compression tests on isotropically consolidated undisturbed block samples of Dhaka clay having OCR values of 1, 2, 5, 10, 15, 20 and 30 in order to develop a correction curve for correcting unconsolidated undrained strength of tube samples of Dhaka clay.

(vi) To investigate the influence of isotropic reconsolidation and anisotropic reconsolidations using Bjerrum (1973) and SHANSEP procedures (Ladd and Foott, 1974) in order to assess the suitability of reconsolidation of both "tube" and "perfect" samples to minimize sampling disturbance effects in reconstituted overconsolidated (OCR values of 2 and 10) Dhaka clay.

The present research will provide a sound understanding of the effects of tube sampling and perfect sampling on the engineering behavior of overconsolidated Dhaka clay. The results will also enable to asses the influence of the design parameters of a tube sampler on the laboratory measured undrained shear properties of overconsolidated Dhaka clay and thereby indicate the appropriate method of sampling in overconsolidated Dhaka clay and to select the appropriate design of sampling tube to be used for undisturbed sampling in overconsolidated Dhaka clay. The present investigation will provide a basis for the selection of appropriate reconsolidation procedure for undisturbed tube samples of overconsolidated Dkaka clay before being sheared for the determination undrained soil parameters for use in analyses and designs. Finally, the present study will provide a basis for reevaluating and possible modifications of existing soil sampling techniques and laboratory testing procedures for determining geotechnical parameters of overconsolidated Dhaka clay.

1.3 THE RESEARCH SCHEME

The whole research work was carried out in accordance with the following phases:

(i) Firstly, sampling tubes having different cutting shoe geometry to investigate tube sampling disturbance effects have been designed and fabricated.

(ii) Secondly, index properties of the Dhaka clay used in this study were determined.

(iii) In the third phase, the engineering properties of "in situ" samples and "tube" samples collected with samplers of varying area ratio and outside cutting edge angle for Dhaka clay (overconsolidation ratios of 1, 2, 5 and 10) were determined by performing undrained triaxial compression tests.

(iv) In the fourth stage, behaviour of "perfect" samples was investigated by modelling "perfect" sampling on "in situ" samples having OCR values of 1, 2, 5 and 10.

(v) In the fifth phase, undrained triaxial compression tests were carried out on isotropically consolidated undisturbed block samples of Dhaka clay having OCR values of 1, 2, 5, 10, 15, 20 and 30.

(vi) Finally, undrained triaxial compression tests were carried out on both isotropically and anisotropically reconsolidated "tube" and "perfect" samples to investigate the suitability of various reconsolidation procedures to minimize the effects of tube sampling disturbance.

1.4 THESIS LAYOUT

Chapter 2 presents the review of sample disturbance for clay soils. The review mainly includes the effects of sample disturbance on undrained shear characteristics of clays, effects of sampler dimensions, cutting shoe geometry and testing methods on sample disturbance. The application of different reconsolidation procedures to minimize sample disturbance and the various methods to correct sample disturbance effects have also been reviewed in this chapter .

The equipment and instrumentation used for the laboratory investigation in order to investigate sample disturbance effects in Dhaka clay are outlined in Chapter 3.

Chapter 4 presents the experimental techniques and procedures used for investigating the effects of sample disturbance on normally consolidated and overconsolidated (OCR values of 2, 5 and 10) reconstituted Dhaka clay.

Undrained triaxial compression test results on "in situ" samples, "tube" samples, "perfect" samples and reconsolidated "tube" and reconsolidated "perfect" samples are presented and discussed in Chapter 5.

Chapter 6 presents the conclusions of the present investigation and recommendations for further research in this field.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The availability of good mechanical soil parameters for geotechnical design depends on careful testing. Testing may be performed in the field or in the laboratory, but in both the cases the most significant factor controlling the quality of the results is likely to be the avoidance of soil or sample disturbance. The mechanisms of sample disturbance have been well understood since 1940s (Hvorslev, 1940 and 1949; Jakobson, 1954; Kallstenius, 1958). Disturbances to soil in its widest sense occur during drilling, during the process of sampling itself and after sampling. A number of different procedures are adopted for measuring, analysing and correcting the effects of soil sampling disturbance and, in order to highlight the importance of the present research, it is necessary to review previous investigations on sample disturbance.

There has been a wide range of reported observations on the effects of sampling procedures on different types of soils. Some direct investigations considered the effects of major causes of disturbances on the stress-strain, strength, stiffness and pore pressure properties of soils while other indirect observations were concerned more with the design, use and maintenance of samplers and the development of sampling techniques. In this chapter, the previous investigations performed on topics related to soil sampling disturbance are reviewed. The effects of sampling disturbance on the mechanical properties of soils, particularly regional clay are presented. The influences of the design parameters, dimensions of sampler and sampling methods on the measured soil parameters are reviewed. Methods of correcting sampling disturbance effects are also presented.

2.2 MECHANISM OF SAMPLE DISTURBANCE

Cohesive soil sample when collected from the ground, transferred to the laboratory and prepared for testing will be subjected to disturbance. The mechanisms associated with this disturbance can be classified as follows:

(1) Changes in stress conditions;

(2) Mechanical deformation;

(3) Changes in water content and voids ratio; and

(4) Chemical changes

Changes in stress conditions occur as the total stresses being applied to the sample of soil change. In its extreme, this is the relaxation of the total horizontal and vertical stresses from their in situ value, to zero, in the laboratory. Mechanical deformations are shear deformations applied to the soil sample while the sample experiences no change in volume. Changes in water content can be an overall swelling or consolidation of the soil sample, or a redistribution of moisture due to the setting up of pore pressure gradients. A change in voids ratio distinct from the above changes in moisture content, is associated with the expansion of gases in the soil sample as a consequence of relaxation of total stresses. These gases either being free in partially saturated soils or in solution in saturated soils. Chemical changes are associated with the change in chemical properties of the soil particles, inter-particle bonding or pore water. These mechanisms can occur at different stages during the process of transferring a soil sample from the ground to the laboratory, and during preparation for testing. Some of the mechanisms occur very quickly, while others are more time dependent. Some of the mechanisms are unavoidable while others can be minimised or even eliminated. The magnitude of the mechanisms is not only dependent on the sampling processes being used, but also on the type of soil being sampled. The effect of these mechanisms can also be different for different soil types.

A geotechnical engineer is fundamentally concerned with the physical stress-strain-strength properties of the soil under investigation. If the effective stress, fabric or structural features in a sample of soil are altered during the sampling process, then the soil sample in the laboratory will no longer exhibit the same physical properties as it would in situ. It is therefore important to understand where, in the sampling and testing process, the aforementioned mechanisms are occurring, and it is necessary to minimise or even eliminate these mechanisms wherever possible. Where these mechanisms are unavoidable, it is important to know what affect, both qualitatively and quantitatively, they have on the physical properties being measured. In addition, it is important to establish whether the effects of these mechanisms on the physical properties being measured can be assessed and corrected.

2.3 CAUSES OF SAMPLE DISTURBANCE

The principal causes of sampling disturbance are as follows (La Rochelle et al, 1981) :

(1) Disturbance of the soil to be sampled before the beginning of sampling as a result of poor drilling operation.

(2) Mechanical distortion during the penetration of the sampling tube into the soil.

(3) Mechanical distortion and suction effects during the retrieval of the sampling tube.

(4) Release of the total in situ stresses.

(5) Disturbance of the soil during transportation, storage and sample preparation.

The first cause can be reduced by sampling with properly cleaned boreholes advanced by using bentonite slurry. The second and third causes are directly associated with sampler design and can be controlled to certain extent. The fourth cause is unavoidable even though its effects may be different depending on the depth of sampling and soil properties. The fifth cause can be reduced by storing samples for minimum time in controlled atmosphere and careful handling of samples during transportation and preparation.

Mechanism and causes of sampling disturbance were summarized by Clayton (1986). Detail descriptions of the disturbances caused during boring, excavating, sampling, transportation, storage and sample preparation were reported by a number of researchers (Hvorslev, 1949; Hight and Burland, 1990; Clayton, 1986; Bjerrum, 1973; Kallstenius, 1971; Schjetne, 1971, Baligh, 1985; Chin, 1986; Baligh et al., 1987; Bozozuk, 1971; Arman and McManis, 1976; La Rochelle et al., 1976; Kirkpatrick and Khan, 1984; Graham et al. 1987; Sone et al., 1971; Shackel, 1971; Kimura and Saitoh, 1982; Baldi et al., 1988; Brand, 1975; Chandler et al., 1993; Siddique, 1990; Hajj, 1990; Hopper, 1992, Sarker, 1994).

2.4 SAMPLING DISTURBANCE EFFECTS IN NORMALLY CONSOLIDATED AND OVERCONSOLIDATED CLAYS

2.4.1 PERFECT SAMPLING

Disturbance caused due to the release of in-situ total stresses is called stress release or perfect sampling disturbance. A sample which has received no disturbance other than that involved with the release of in situ total stresses is termed "perfect" sample. The influence of perfect sampling on undrained stress-strain, strength, stiffness and pore pressure properties of normally consolidated and overconsolidated clays has been studied by numerous investigators (Ladd and Lambe, 1963; Skempton and Sowa, 1963; Ladd and Varallyay, 1965; Kirkpatrick and Khan, 1984; Kirkpatrick et al., 1986; Siddique and Farooq 1996; Bashar et al., 1997a; Siddique and Sarker 1998; Hight et al., 1985).

Ladd and Lambe (1963) determined values of isotropic effective stress, σ'_{ps} and pore pressure parameter, A_u of "perfect" specimens of Kawasaki Clay and Boston Blue Clay. The resulting values of the ratio, σ'_{ps}/σ'_v were 0.56 ± 0.05 with corresponding A_u values of 0.17 ± 0.10. Similar test data on normally consolidated Boston Blue Clay yielded $\sigma'_{ps}/\sigma'_v = 0.59$ and $A_u =$ 0.11. Skempton and Sowa (1963) reported values of the ratio, σ'_{ps}/σ'_v were 0.57 and 0.67 with corresponding A_u values of -0.02 and -0.10 for overconsolidated clays of Weald (OCR = 2) and Weald (OCR = 14) respectively. Ladd and Varallyay (1965) also reported values of A_u, 0.12 to 0.24 and σ'_{ps}/σ'_v, 0.57 to 0.67 for remoulded Boston Blue Clay. Kirkpatrick et al. (1986) reported values of the ratio, σ'_{ps}/σ'_v were 0.48, 0.38 and 0.20 with corresponding A_u values of 0.25, 0.20 and 0.20 for overconsolidated clays of Kaolin (OCR=2), Illite (OCR=2.7) and Illite (OCR=5) respectively.

Siddique and Farooq (1996) reported values of the ratio, σ'_{ps}/σ'_v were 0.55 to 0.58 with A_u values of 0.10 to .13 for normally consolidated soft Chittagong coastal soils (LL = 43 to 57, PI = 18 to 33). Bashar et al. (1997a) also reported values of the ratio, σ'_{ps}/σ'_v were 0.54 to 0.57 with A_u values of 0.125 to 0.140 for other normally consolidated firm coastal soils (LL = 34 to 55, PI = 10 to 20). Siddique and Sarker (1998) reported values of the ratio, σ'_{ps}/σ'_v were 0.65 with corresponding A_u values of 0.13 for reconstituted normally consolidated soft Dhaka (LL = 45, PI = 23). The values of σ'_{ps} and A_u of "perfect" samples, and the ratio σ'_{ps}/σ'_v for "perfect" sampling obtained by different investigators are summarised in Table 2.1.

Skempton and Sowa (1963) examined the effect of "perfect" sampling in remoulded Weald Clay (LL = 46, PI = 24) which has a low sensitivity ($S_t = 2$). Skempton and Sowa (1963) found that the undrained strength of the normally consolidated "perfect" samples were only 2% less than that of the "ground" samples although the stress paths were entirely different. They also found that failure strain of "perfect"samples were increased. Skempton and Sowa (1963) found that the undrained strength of the overconsolidated "perfect" samples were 3% and 8% more than that of the "ground" samples for Weald clay (OCR=2) and Weald clay (OCR=14) respectively.

Noorany and Seed (1965) observed a 5% reduction of the undrained strength, 5% increase in strain at peak strength and 10% reduction of the initial stiffness for normally consolidated "perfect" samples of soft clay (LL = 88, PI = 45). Ladd and Varallyay (1965) found a 7% decrease in undrained strength and 150% increase (highly) in the strain at peak strength for normally consolidated Boston Blue Clay (LL = 33, PI = 15) due to "perfect" sampling. Davis and Poulos (1967) reported a 19% decrease in undrained strength of a remoulded "perfect" kaolin (LL = 55, PI = 22) specimen tested unconfined.

Kirkpatrick and Khan (1984) reported that 56% and 38% reduction of the undrained strength, 175% and 250% increase in strain at peak strength, 24% and 22% decrease in the initial stiffness obtained for normally consolidated clays of Kaolin (PI = 30) and Illite (PI = 40) respectively due to "perfect" sampling. Kirkpatrick et al. (1986) reported that 48%, 38%, and 14% reduction of the undrained strength, 75%, 150% and 10% increase in strain at peak strength, 68%, 73% and 6% decrease in the initial stiffness yielded for the overconsolidated clays of Kaolin (OCR = 2.0), Illite (OCR = 2.7) and Illite (OCR = 5.0), respectively due to perfect sampling. Fig. 2.1 shows the plot of C_{up}/ C_{ui} (s_u of perfect sample / s_u of in situ sample) versus OCR of "perfect" samples of Illite. Kirkpatrick et al. (1986) reported from Fig. 2.1 that the undrained strength (s_u) increased with increasing OCR for "perfect" samples.

The effects of perfect sampling on undrained behaviour of a young normally consolidated and overconsolidated (OCR=7.4) low plasticity clays (LL = 32, PI = 17) from North Sea have been discussed by Hight et al (1985). Perfect sampling disturbance greatly reduced the initial mean effective stresses. Peak undrained strength of both normally consolidated and overconsolidated samples were reduced due to perfect sampling. The effective stress changes during "perfect" sampling were completely different for the two stress histories considered. The effect of "perfect" sampling disturbance on overconsolidated (OCR = 2.5) plastic Drammen Clay (PI = 27) has been reported by Lacasse and Berre (1988). They reported about 11% decrease in undrained shear resistance in compression.

Table 2.1 A_u-values and Stress Ratios ($\sigma_{ps}'/\sigma_{vc}'$) for "Perfect" samples of Normally Consolidated and Overconsolidated Clays

Clay Type	Index Properties	K_0	A_u	$\sigma_{ps}'/\sigma_{vc}'$	Reference
Undisturbed Kawasaki clay	LL = 48 – 106 PI = 16 – 46	0.47	0.07 to 0.28	0.51 to 0.61	Ladd and Lambe (1963)
Undisturbed Boston Blue clay	LL = 33 PI = 14	0.54	0.11	0.59	
Remoulded weald clay	LL = 46 PI = 24 S_t = 20	0.59	-0.02 to –0.1	0.57 to 0.61	Skempton and Sowa (1963)
Undisturbed San Francisco Bay Mud	LL = 88 PI = 45 S_t = 10	0.50	0.16 to 0.24	0.58 to 0.62	Seed et al. (1964)
Remoulded Boston Blue clay	LL = 33 PI = 15 $S_t = 7 \pm 2$	0.54	0.12 to 0.24	0.57 to 0.67	Ladd and Varallyay (1965)
Kaolin, OCR= 2	PI = 30	0.85	0.25	0.48	Kirkpatrick et al.(1986)
Illite, OCR=2.67	PI = 40	1.0	0.20	0.38	
Illite, OCR=5	PI = 40	1.0	0.20	0.20	
Kaolin, OCR= 1	PI = 30	0.56	0.25	1	
Illite, OCR=1	PI= 40	0.67	0.20	1	
Reconstituted Patenga clay	LL = 44 PI = 18	0.49	0.133	0.56	Siddique and Farooq (1996)
Reconstituted Fakirhat clay	LL = 43 PI = 22	0.50	0.10	0.55	
Reconstituted Kumira clay	LL = 57 PI = 33	0.52	0.117	0.58	
Reconstituted Banskhali clay	LL = 34 PI = 10	0.47	0.132	0.54	Bashar et al. (1997a)
Reconstituted Anwara clay	LL = 40 PI = 16	0.49	0.125	0.55	
Reconstituted Chandanaish clay	LL = 45 PI = 20	0.50	0.140	0.57	
Reconstituted Dhaka clay	LL = 45 PI = 23	0.60	0.13	0.65	Siddique and Sarker (1998)

Apart from leading to a decrease in strength, "perfect" sampling has a marked influence on pore pressure responses as reported by Seed et al (1964), Noorany and Seed (1965), and Ladd and Varallyay (1965). The pore pressure parameter A at failure was found to decrease by as much as 50% for specimens subjected to perfect sampling. Ladd and Varallyay (1965) also observed a slight reduction in stiffness and a large increase in axial strain required to mobilise the peak shearing resistance. Atkinson and Kubba (1981) also reported considerably lower stiffness for anisotropically consolidated "perfect" specimens than that for the "in-situ" specimens.

The effects of perfect sampling disturbance on mechanical properties of normally consolidated and overconsolidated clays, as reported by a number of investigators are summarised in Table 2.2 .

Siddique and Farooq (1996) and Bashar et al. (1997a) investigated the influence of perfect sampling disturbance on undrained shear properties of reconstituted normally consolidated coastal soils. Reductions in undrained strength (s_u) and pore pressure parameter A at peak deviator stress, A_p while increase in axial strain at peak deviator stress (ε_p), initial stiffness (E_i) and secant stiffness at half the paek deviator sress (E_{50}) have been reported due to perfect sampling. Fig. 2.2 shows the stress paths of "perfect" and "in situ" samples of the samples of two coastal soils investigated by Siddique and Farooq (1996). It can be seen from Fig. 2.2 that the "perfect" samples adopted stress paths completely different from the "in situ". Effective stress paths of "perfect" samples are similar to those for overconsolidated samples.

Bashar et al. (1997a) also reported that the effective stress paths of "perfect" and "in situ" samples were markedly different. Fig. 2.3 shows the secant stiffness versus axial strain plots of "perfect" and "in situ" samples of three coastal soils studied by Bashar et al. (1997a). It can be seen from Fig. 2.3 that, in general, secant stiffnesses of "in situ" and "perfect" samples reduced with the increase in axial strain and secant stiffesses (at all strain levels) of the "perfect" sample are considerably higher than those for the "in situ" samples. Fig. 2.4 shows the pore pressure parameter at peak strength, A_p with axial strain plots of "perfect" and "in situ" samples of three coastal soils. It can be seen from Fig. 2.4 that compared with the "in situ" samples, the values of A_p of "perfect" samples are considerably less.

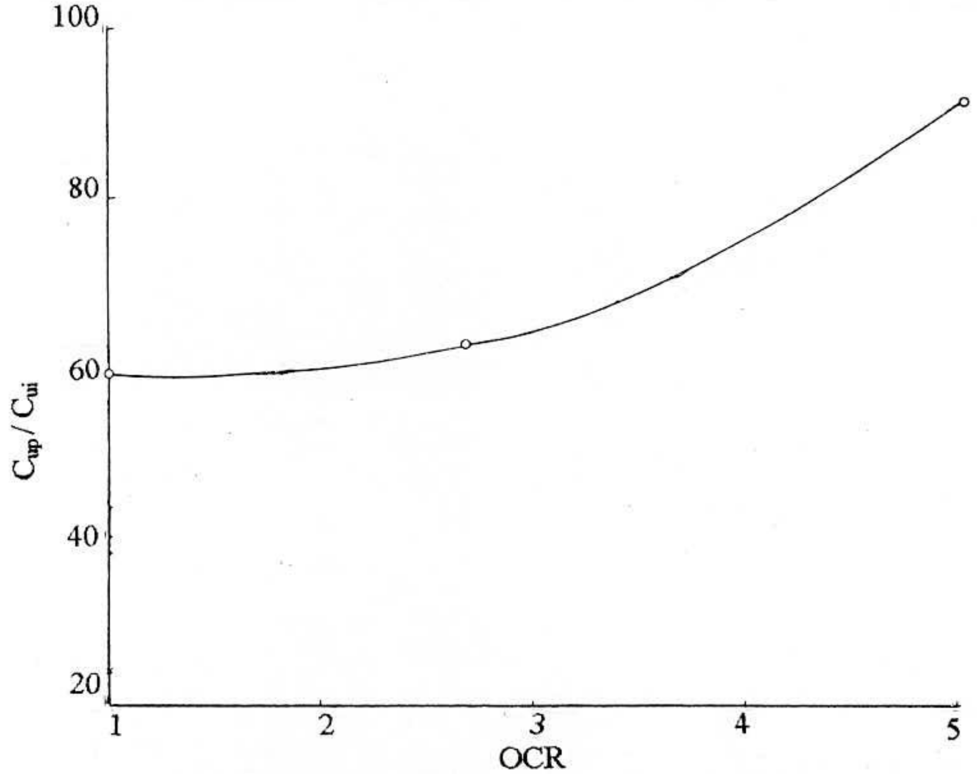


Fig.2.1 Variation of the ratio of C_{up} / C_{ui} with OCR of "perfect" samples of Illite (after Kirkpatrick et al., 1986).

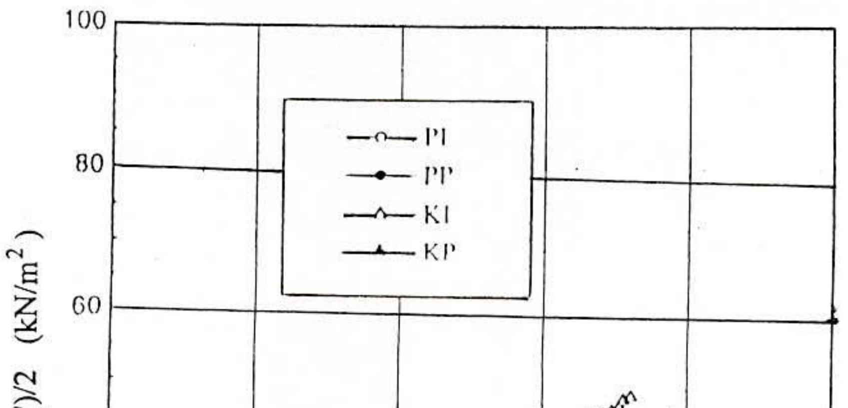


Fig.2.2 Effective stress paths of "perfect" and "in situ" samples from Patengha and Kumira (after Siddique and Farooq, 1996).

Table 2.2 Summary of the Effects of "Perfect" Sampling Disturbance on Some Mechanical Properties of Normally Consolidated and Overconsolidated Clays

Soil	Index values	OCR	Ratio of s_u	Ratio of ε_p	Ratio of E_i	Ratio Of E_{50}	Ratio of A_p	Reference
Weald Clay	LL = 46 PI = 24	1.0	0.98	1.29	-	-	-	Skempton and Sowa (1963)
		2.0	1.03	0.88	-	-	-	
		14.0	1.08	-	-	-	-	
Soft Clay	LL = 88 PI = 45	1.0	0.95	1.05	0.9	-	-	Noorany and Seed (1965)
Boston Blue Clay	LL = 33 PI = 15	1.0	0.93	2.5	-	-	-	Ladd and Varallyay (1965)
Kaolin	LL = 55 PI = 22	1.0	0.81	-	-	-	-	Davis and Poulos (1967)
Kaolin	PI = 30	1.0	0.44	2.75	0.76	-	-	Kirkpatrick and Khan (1984)
Illite	PI = 40	1.0	0.58	3.50	0.78	-	-	
North Sea Clay	LL = 32 PI = 17	1.0	0.72	8.00	1.19	-	-	Hight et al. (1985)
		7.4	0.96	1.00	0.47	-	-	
Kaolin	PI = 30	2.0	0.54	1.75	0.46	-	-	Kirkpatirick et al. (1986)
Illite	PI = 40	2.7	0.62	2.50	0.52	-	-	
Illite	PI = 40	5.0	0.86	1.10	0.94	-	-	
Patengha Clay	LL = 44 PI = 18	1.0	0.87	1.32	1.40	-	0.32	Siddique and Farooq (1996)
Kumira Clay	LL = 57 PI = 33	1.0	0.93	1.24	1.47	-	0.17	
Banskhali Clay	LL = 34 PI = 10	1.0	0.89	1.27	1.06	1.10	0.54	Bashar et al. (1997a)
Anwara Clay	LL = 40 PI = 16	1.0	0.92	1.21	1.08	1.07	0.50	
Chandan-aish clay	LL = 45 PI = 20	1.0	0.96	1.17	1.09	1.08	0.44	
Dhaka Clay	LL = 45 PI = 23	1.0	0.97	1.16	1.67	1.40	0.36	Siddique and Sarker (1998)

Note: All ratios referred to results from "in situ" samples.

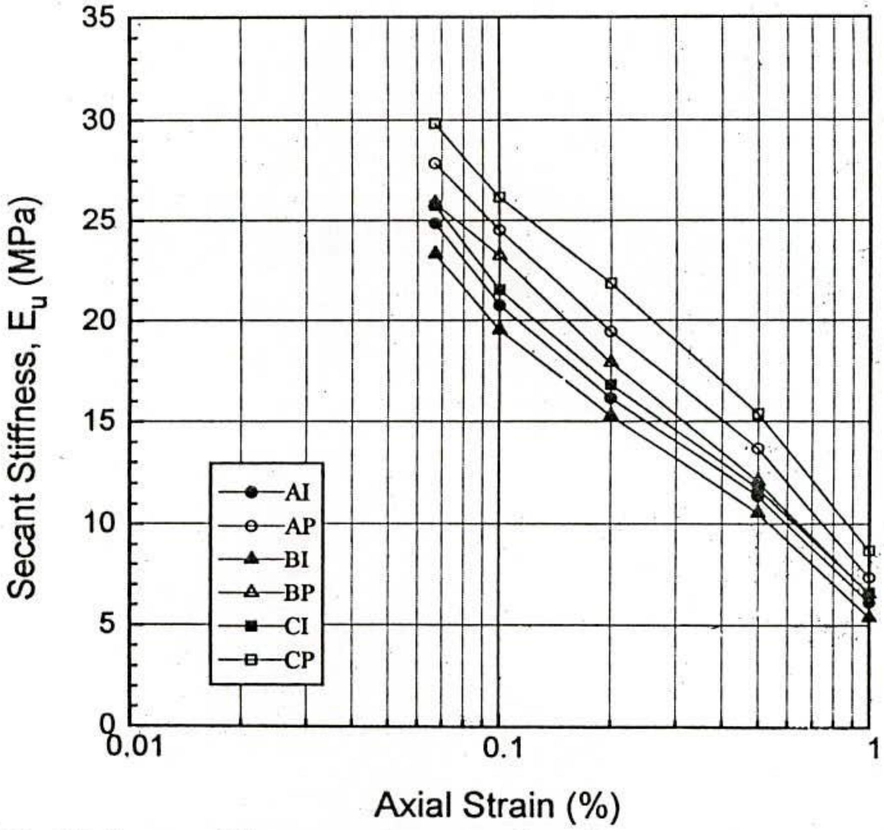


Fig.2.3 Secant stiffness vs. axial strain of "perfect" and "in situ" samples from three coastal soils (after Bashar et al. 1997a).

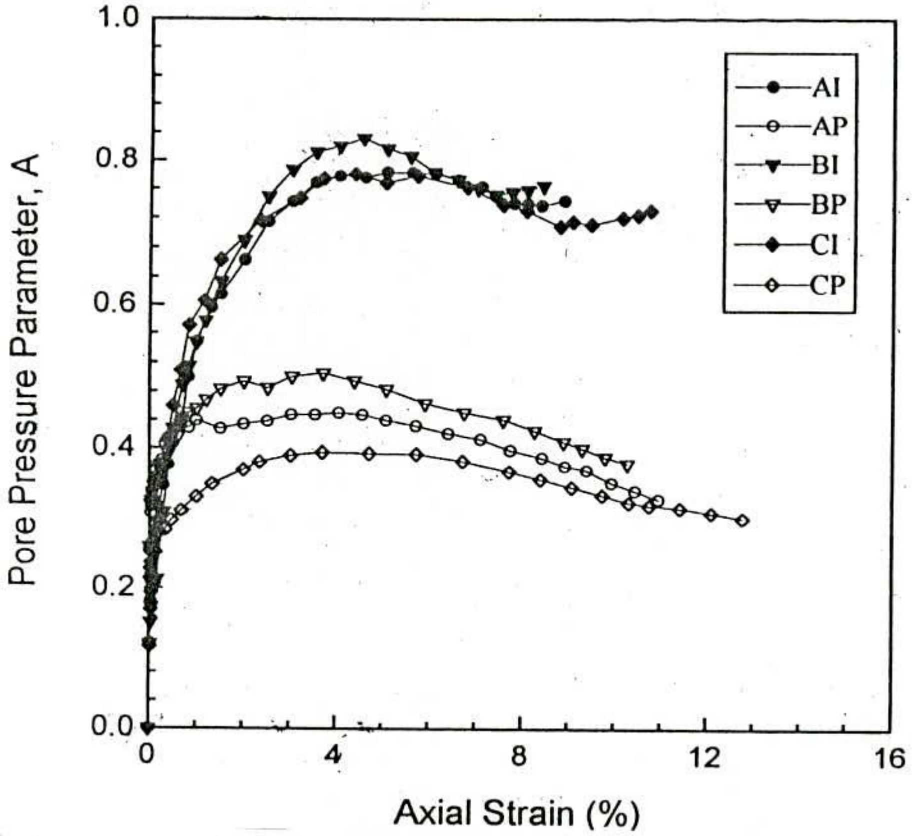


Fig.2.4 Comparison of pore pressure parameter, A vs. Axial strain plots of "perfect" and "in situ" samples from three coastal soils (after Bashar et al, 1997a).

Siddique and Sarker (1998) investigared the effects of "perfect" sampling on undrained shear properties of reconstituted normally consolidated soft Dhaka clay (LL = 45, PI = 23). Fig.2.5 shows the deviator stress versus axial strain plots of "perfect" and "ground" samples of Dhaka clay. It can be seen from Fig. 2.5 that deviator stress of the "perfect" sample are lower than that of the "in situ" samples resulting in reduction in undrained strength. Increase in ε_p, initial stiffness and secant stiffness has also been reported. The value of A_p, however, reduced due to perfect sampling in Dhaka clay.

The effect of stress history on the perfect sampling stress path and on the changes in mean effective stress was reported by Hight and Burland (1990) for the case of a low plasticity clay. This is shown in Fig. 2.6. It can be seen from Fig. 2.6 that the effective stress changes reduce as the OCR increases; for an OCR of 4, there is no change in effective stress; for the heavily overconsolidated clay, there is a slight increase in average effective stress. Therefore, the effect of perfect sampling on undrained triaxial compression strength decreases with increasing OCR as shown in Fig. 2.7.

2.4.2 TUBE SAMPLING

The response that could be anticipated in normally consolidated soil after tube sampling and extrusion has been investigated by Hight et al. (1987) for young low to medium plasticity clays. It has been found that the undrained stress path and stress-strain curve of "tube" sample are markedly different from those of "perfect" and "in-situ" samples. Hight et al. (1985) also reported the behaviour of three "tube" samples taken from the sea bed in the North Sea. The estimated OCR's of the first two samples were 1.1 and the OCR of the third sample was greater than 50. The initial mean effective stresses of the normally consolidated samples were below those estimated in situ, but the heavily overconsolidated sample showed a large overall increase in initial mean effective stress. None of the three intact tests provided a satisfactory model for the in-situ behaviour.

The effects of tube sampling disturbance on undrained shear properties of reconstituted normally consolidated soft samples of Dhaka clay (Siddique abd Sarker, 1995) and three coastal soils (Siddique et al., 2000) are summarised in Table 2.3. It can be seen from Table 2.3 that disturbance due to tube sampling caused reduction in undrained shear strength (s_u),

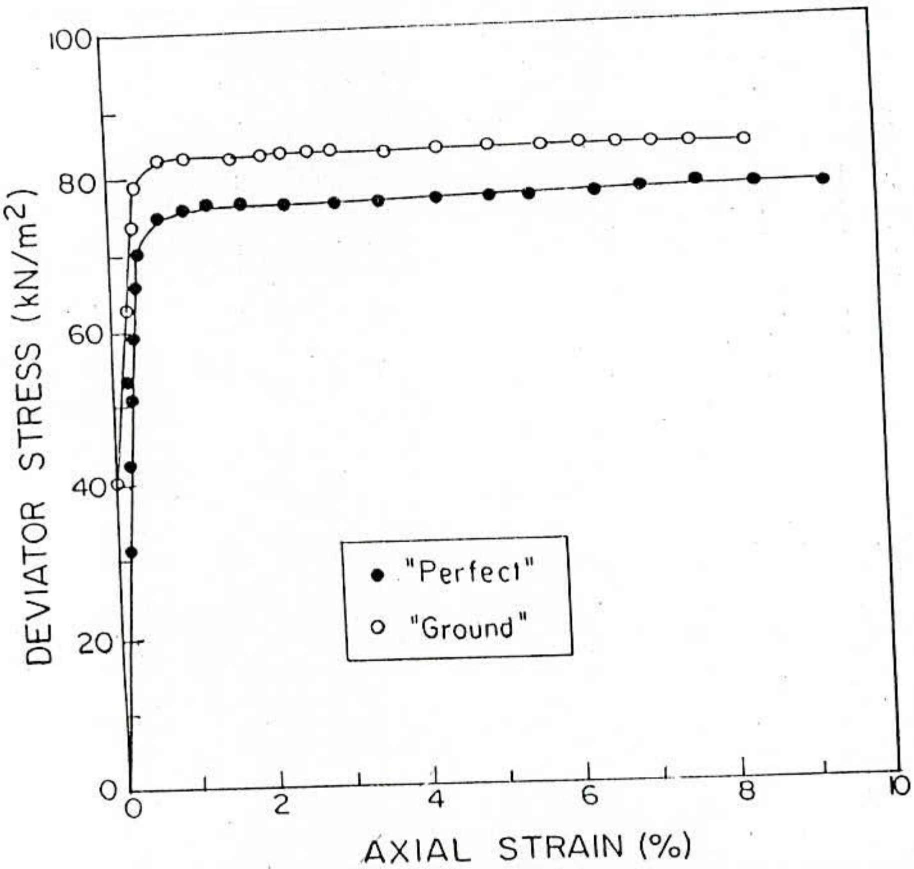


Fig.2.5 Deviator Stress versus axial strain plots for "perfect" and "ground" samples of Dhaka clay (after Siddique and Sarker, 1998).

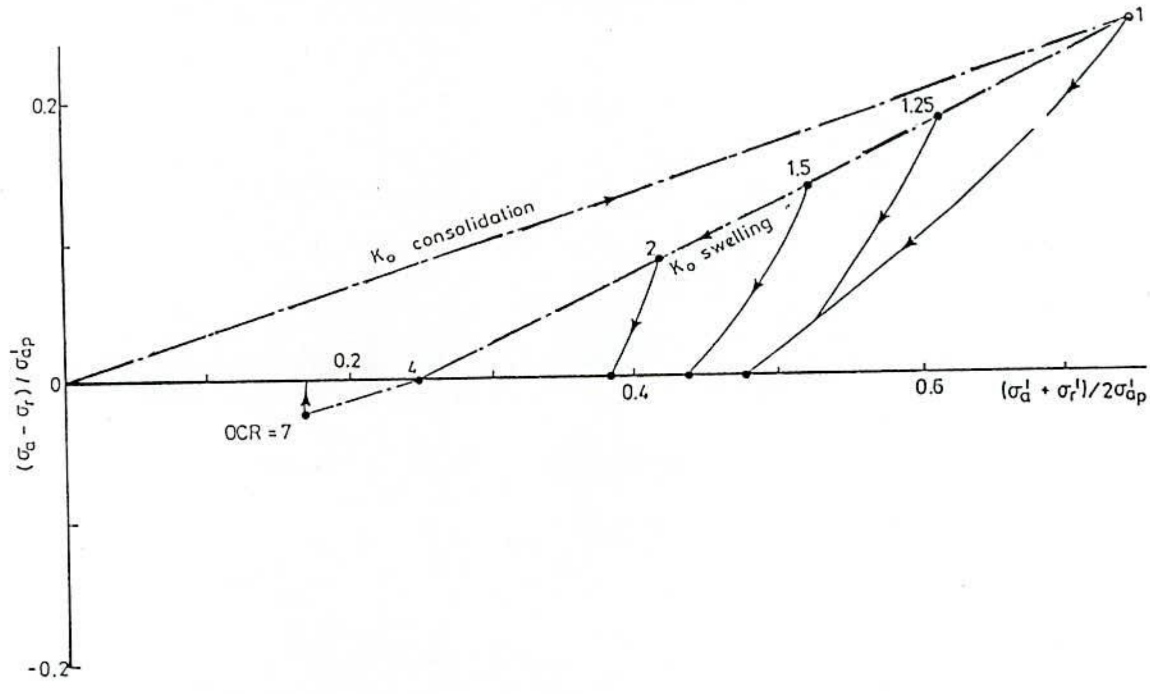


Fig.2.6 Effect of stress history on "perfect" sampling stress path for low Plasticity clay (after Hight and Burland, 1990).

initial stiffness (E_i), secant stiffness at half the peak deviator stress (E_{50}) and Skempton's pore pressure parameter A at peak deviator stress (A_p). Axial strain at peak deviator stress (ε_p), however, increased due to tube sampling disturbance.

Table 2.3 Effects of Tube Sampling Disturbance on Mechanical Properties of Regional Soils of Bangladesh.

Soil location	Index values	Change in properties compared with "in-situ" sample					Reference
		Reduction in s_u (%)	Increase in ε_p (%)	Reduction in E_i (%)	Reduction in E_{50} (%)	Reduction in A_p (%)	
Dhaka	LL = 45 PI = 23	17 – 35	35 – 81	11 – 49	1 – 34	106 – 111	Siddique and Sarker(1995)
Patengha	LL = 44 PI = 18	42 – 55	19 – 78	34 – 74	-	115 – 123	Siddique et al. (2000)
Fakirhat	LL = 43 PI = 22	34 – 55	4 – 32	31 – 70	-	101 – 115	
Kumira	LL = 57 PI = 33	34 – 56	4 – 13	31 – 76	-	102 – 117	

Fig. 2.8 shows the deviator stress versus axial strain plots of "tube" and "ground" samples of Dhaka clay. It can be seen from Fig. 2.8 that, deviator stress of the "tube" samples are considerably lower than that of the "in situ" sample resulting in reduction in undrained strength. Figs. 2.9 (a) and (b) show the effective stress paths of samples of Dhaka clay and coastal soil from Kumira, respectively. It can be seen from Figs. 2.9 (a) and (b) that, "tube" samples adopted stress paths completely different from the normally consolidated "in situ" samples. Effective stress paths of "tube" samples are similar to those for overconsolidated samples. Fig. 2.10 shows the variation of pore pressure change with axial strain for "tube" and "in situ" samples of a coastal soil. It can be seen from Fig. 2.10 that compared with the "in situ" sample, the values of pore pressure changes of the "tube" samples are considerably less.

2.4.3 IDEAL SAMPLING

New insights into tube sampling disturbance have been made possible using the Strain Path Method (Baligh 1985). Baligh (1985) used the Strain Path Method to predict the strains that would be set up by a "simple sampler" with external diameter (B) to thickness (t) ratio, i.e.,

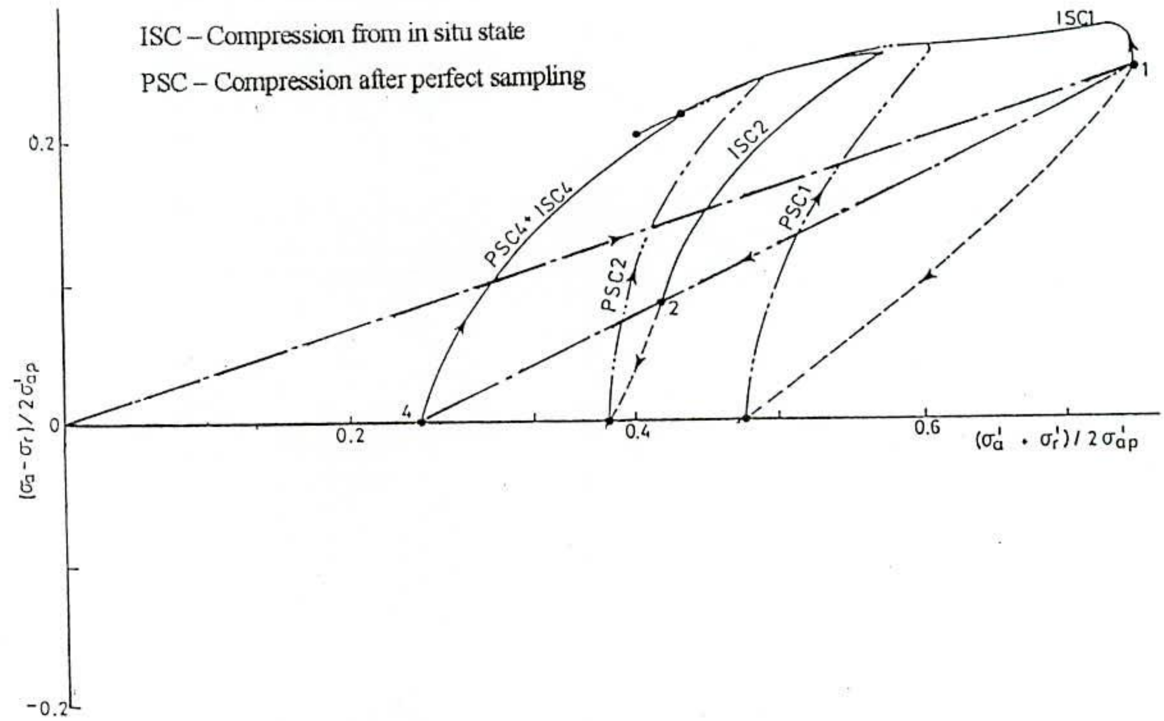


Fig.2.7 Effect of stress history on undrained triaxial compression strength for "perfect" sampling in low plasticity clay (after Hight and Burland, 1990).

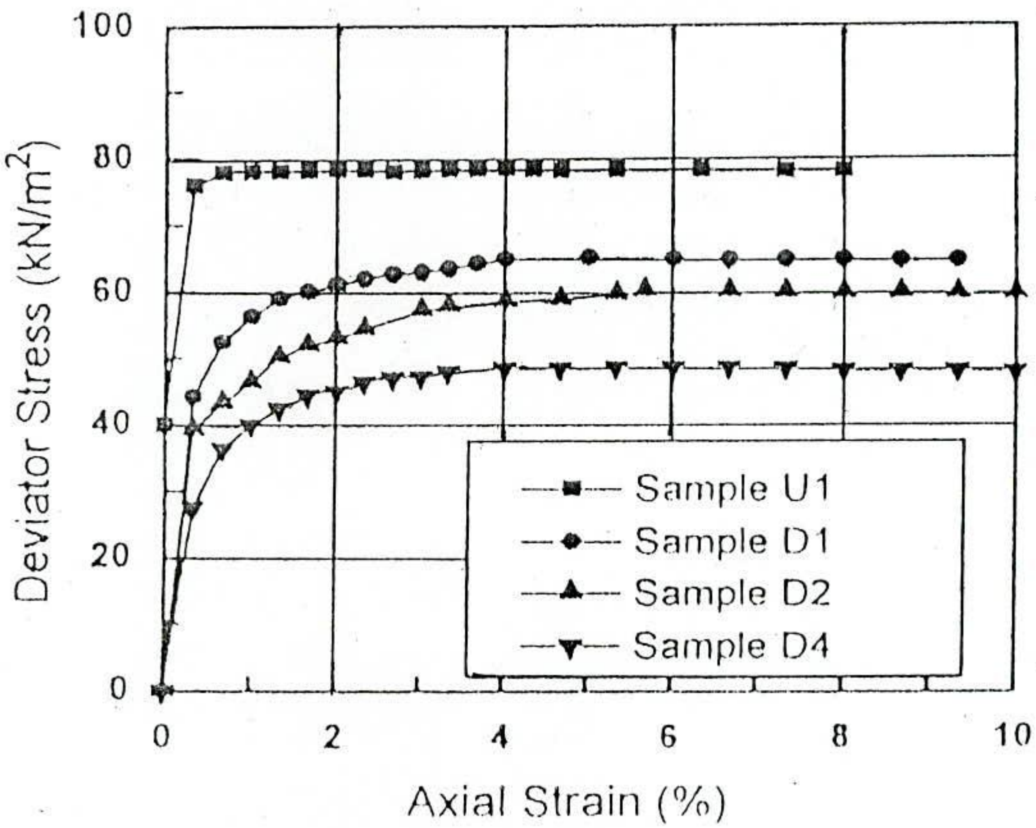
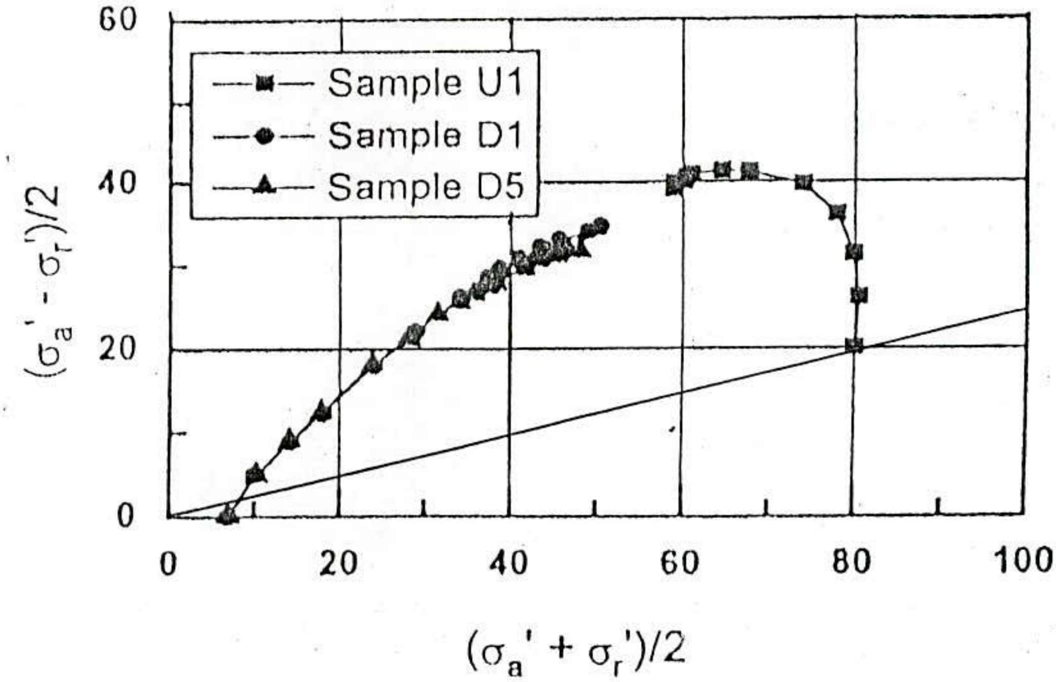
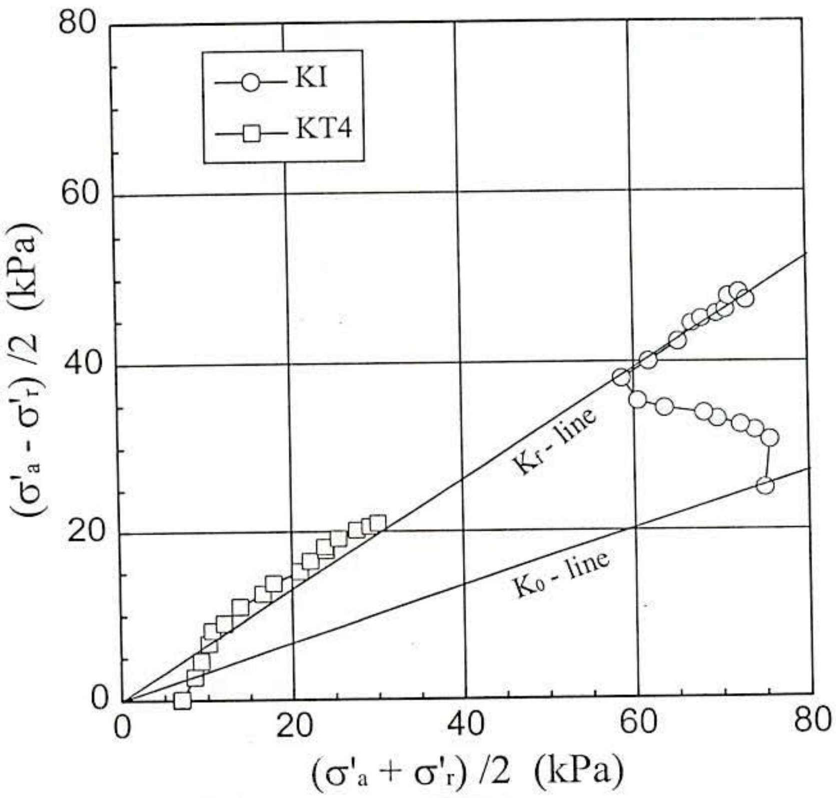


Fig.2.8 Deviator stress versus axial strain plots for "tube" samples for Dhaka clay (after Siddique and Sarker, 1995).



(a)



(b)

Fig.2.9 Comparison of typical effective stress paths between the "in situ" and "tube" samples: (a) Dhaka clay (after Siddique and Sarker, 1995), (b) Kumira soil (after Siddique et al. 2000).

B/t ratios varying from 10 to 40. Fig. 2.11 shows predicted strains for B/t values of 10, 20, and 40. For this particular tube geometry, Baligh (1985) predicted that strain excursions on the centerline of the sample would have maximum values in axial compression and extension of between 0.75% and 4.0%.

Baligh et al. (1987) proposed ideal sampling approach (ISA) as an extension to "perfect" sampling. Ideal sampling approach denotes an idealised method of incorporating the effects of tube penetration, sample retrieval to the surface and extrusion from the tube, but neglects all other types of disturbances, including operator dependent disturbances and water content changes in the soil. The proposed method for implementing ISA consists of the following steps:

(i) Estimation of tube penetration disturbances at the centreline of sampler using the Strain Path Method (Baligh, 1985).
(ii) Estimating the effects of sample retrieval and extrusion by assuming an idealised process of undrained stress relief from the (generally) anisotropic stress conditions in the tube to the final isotropic stress state of the sample before testing.

Step (ii) adopts the same simplification adopted by "perfect" sampling regarding sample retrieval and extrusion simulation. Therefore, the only difference between the proposed ISA and "perfect" sampling is the incorporation of tube penetration disturbances, i.e., step (i), and hence ISA is equivalent to "perfect" sampling when tube penetration disturbances are insignificant.

Hight (1986) pointed out the following effects due to ideal sampling:

(i) in the normally consolidated soil, the effective stresses are reduced;
(ii) in the heavily overconsolidated soil, the effective stresses are increased;
(iii) changes in pore pressure are different on the centreline and around the periphery so that a process of equalisation takes place.

The level of distortion which occurs around the periphery of tube samples is often apparent when such a sample is split to expose its fabric. Although the strain paths followed in this outer zone have not been modelled in triaxial tests, it can be reasonably anticipated that:

(a) soil in an initially normally consolidated or lightly overconsolidated state will develop positive pore pressure increments.
(b) soil in a heavily overconsolidated state will develop negative pore pressure increments Extrusion involves additional distortion.

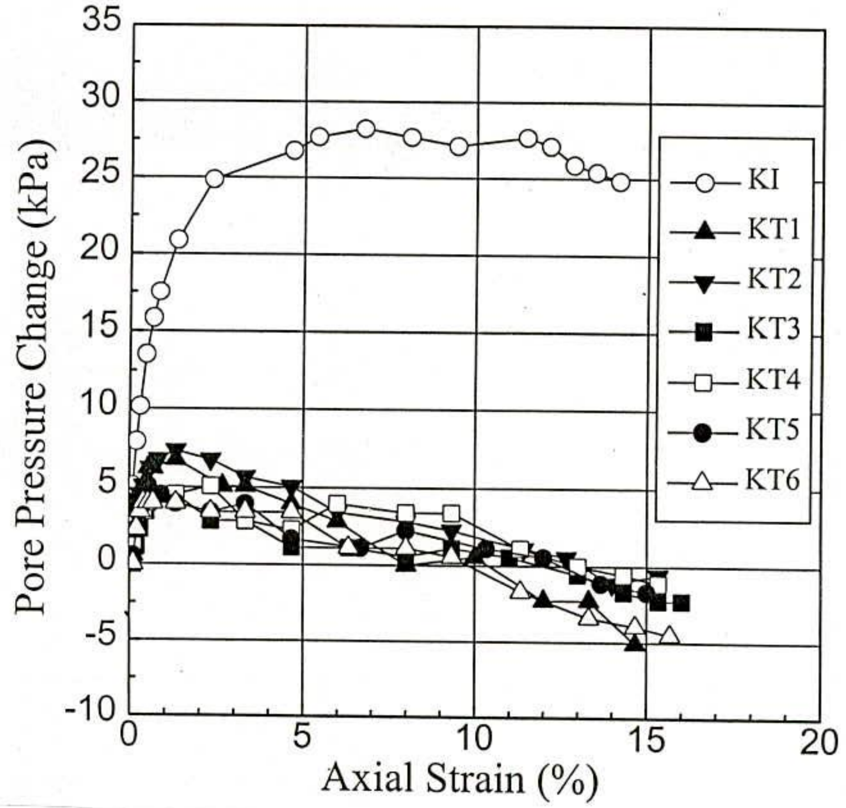


Fig.2.10 Comparisons of typical pore pressure response between the "in situ" and "tube" samples of Kumira soil (after Siddique et al, 2000).

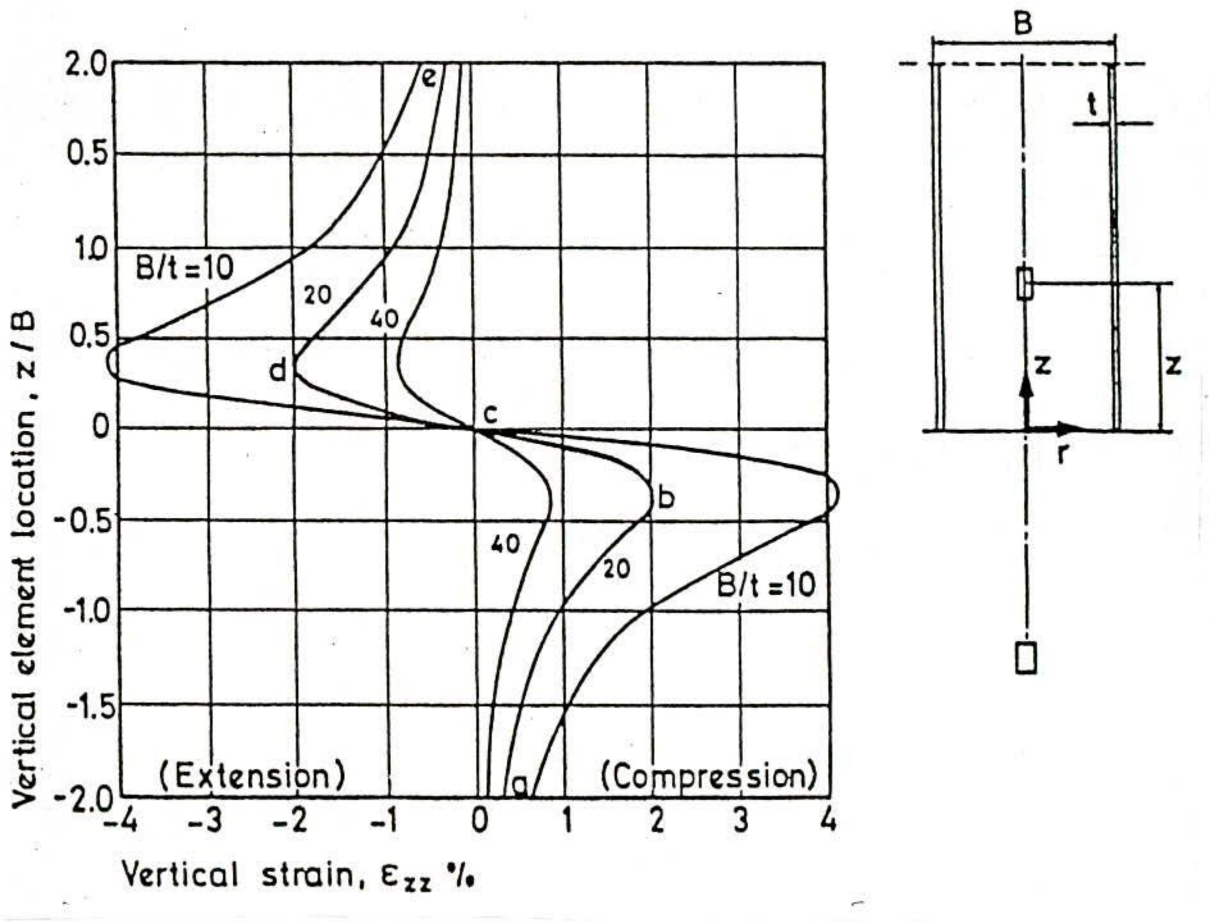


Fig.2.11 Strain paths for element on the centreline of a tube sampler (after Baligh, 1985).

Because of axial symmetry, the effects of the predicted tube sampling strains on soil properties can be examined by applying them to a triaxial specimen in the form of compression, followed by extension, test phases. In most of these studies, strain path excursions of amplitude ±1% have been applied to reconstituted clays. This is equivalent to imposing the strains predicted along the centerline of a simple sampler with B/t = 40 and an inside clearance ratio of about 1%. The reported results show marked changes in mean effective stress, peak undrained shear strength, strain at failure, and undrained stiffness between the "undisturbed" samples and samples to which tube penetration disturbances or ideal sampling disturbances have applied: Progressive destructuring and changes in the yield surface have also been observed in natural (bonded) clays (Clayton et al. 1992).

Table 2.4 shows a summary of previous results- materials that have not been reconstituted will nonetheless have undergone some disturbance and restructuring due to sampling. It can be seen that although very large decreases in mean effective stress (p'_0) have been observed, particularly for normally consolidated reconstituted clays, the associated reductions in undrained shear strength (s_u) have not been particularly great. Indeed, it seems likely that if samples are reconsolidated to their effective stress before sampling, the decrease in void ratio may lead to an increase in s_u, as found by Hajj (1990). But the decreases in stiffness caused by a reduction in mean effective stress are likely to be high. Baligh et al. (1987) found 59% reduction in p'_0 in normallly consolidated reconstituted Boston Blue clay (LL = 42, PI = 20) while in slightly overconsolidated natural Bothkennar clay (LL = 76, PI = 42), Clayton et al. (1992) found that p'_0 reduced by 43% due application of tube sampling strains of amplitude ±1%. In the natural overconsolidated Vallericca clay (LL =53, PI = 31) and London clay (LL =60, PI = 32), Georgiannou and Hight (1994) found that p'_0 reduced by 10%. In reconstituted normally consolidated Speswhite kaolin (LL = 72, PI = 32). Hird and Hajj (1995) reported 50% to 60% reduction in p'_0 while in the reconstituted normally consolidated London clay (LL = 69, PI = 45), Siddique et al. (1999) found 10 % to 37% reduction in p'_0. Baligh et al. (1987) have reported a 21% reduction in undrained strength ratio (s_u / σ'_{vc}) for reconstituted Boston Blue clay due application of tube sampling strains of amplitude ±1%. Wei et al. (1994) found a reduction in s_u of about 14% for normally consolidated reconstituted mixture of kaolin (80%) and silty sand (20%). Siddique et al. (1999) found a reduction of 2% to 6% in s_u in reconstituted London clay. In Vallericca and London clays, Georgiannou and Hight (1994) found that s_u reduced by less than 5% while in Bothkennar clay, Clayton et al. (1992) reported that s_u reduced by 5%. Siddique et al. (1999) found that ε_p increased up to 127% due to application of tube sampling strains of amplitude ± 1% in reconstituted London clay. Baligh et al. (1987) and Wei et al. (1994) also reported significant increase in ε_p, 27 times and 10 times, respectively. For strain path excursion of amplitude ±1%, Baligh et al. (1987) reported decrease in undrained modulus ratio, E_{50} / σ'_{vc} (where E_{50} is the secant stiffness at half the peak deviator stress) of as much as 95%.

Lacasse and Berre (1988) also reported reductions in initial moduli for normally consolidated and overconsolidated specimens of Drammen clay due to the application of equivalent tube-sampling strains. For Bothkennar clay, Clayton et al. (1992) reported a reduction in normalized secant stiffness at 0.1% axial strain of between 30% and 61%, when the amplitude of the strain cycle was greater than ±0.5%. However, an increase in stiffness of 32% was found following a strain cycle of amplitude ±0.5%, which was attributed to reduction in water content during reconsolidation more than compensating for any damage to the structure due to disturbances during path cycles. In overconsolidated reconstiuted Vallericca and London clays, Georgiannou and Hight (1994) have reported reductions of stiffness at 0.01% axial strain of 35% and 25%, respectively.

In reconstituted normally consolidated clayey sand, Hight and Georgiannou (1995) found minor effects on small-stiffness due to the application of tube sampling strains of amplitudes ±0.5% and ±1%. Siddique et al. (1999) reported that values of E_i, E_{50} and A_p reduced by 77%, 65% and 78% provided in reconstituted London clay due application of tube sampling strains of amplitude ±1%. For overconsolidated London clay (OCR = 3.7), Siddique et al. (1999) reported a reduction in effective stress 10.5% and reduction in undrained shear strength 6% while increase in strain at peak strength 56%.

Hopper (1990) concluded that ideal sampling caused relatively little degree of disturbance to reconstituted overconsolidated London clay, compared with reconstituted normally consolidated London clay.

Table 2.4 Effects of Ideal sampling on undrained shear properties of normally consolidated (NC) and overconsolidated (OC) clays.

Soil type	Atterberg Limits (%)		OCR	Change in properties (%)			Reference
	LL	PI		Reduction in σ'_i	Reduction in s_u	Increase in ε_p	
Boston Blue Clay	42	20	1.3	59	21	5-18	Baligh et al. (1987)
Lightly OC Drammen Clay	-	27	2.5	-	0	-	Lacasse and Berre (1988)
Speswhite Kaolin	72	32	4	11	-16	-	Hajj (1990)
Bothkennar OC Clay	76	42	1.4-1.6	43	½-10	35	Clayton et al. (1992)
OC Vallerica and London clays	53 60	31 32	- -	10	<5	20	Georgiannou and Hight (1994)
NC Sandy kaolin	-	-	1	-	14	7-10	Wei et al. (1994)
NC Speswhite Kaolin	72	32	1	50-60	-	10	Hird and Hajj (1995)
NC London clay	69	45	1	10-37	2-7	30-313	Siddique et al. (1999)
OC London clay	86	61	3.7	10.5	6	56	

2.5 SAMPLER DESIGN AND ITS EFFECT ON SAMPLE DISTURBANCE

The design of a sampler is one of the most important factors that should be considered for quality sampling. The amount of disturbance varies considerably depending upon the dimensions of the sampler and the precise geometry of the cutting shoe of the sampler. Hvorslev (1949) discussed at length importance of the design of a sampler and introduced the concepts of area ratio, inside and outside clearance ratios and cutting edge taper angle in controlling sampling disturbance.

2.5.1 EFFECT OF AREA RATIO AND CUTTING EDGE TAPER ANGLES

Area ratio is considered one of the critical parameters affecting the disturbance of soil during sampling. Hvorslev (1949) defined area ratio as follows:

$$Area\ Ratio = \frac{D_w^2 - D_i^2}{D_i^2} \quad \ldots (2.1)$$

Where D_w is the external diameter of the sampler tube and D_i is the internal diameter of the sampler cutting edge as shown in Fig. 2.12. Increasing area ratio gives increased soil disturbance and remoulding. The penetration resistance of the sampler and the possibility of the entrance of excess soil also increase with increasing area ratio. For soft clays, area ratio is kept to a minimum by employing thin-walled tubes.

For composite samplers, the area ratio, however, is considerably higher. In these cases, sample disturbance is reduced by tapering the outside of the sampler tube very gradually from a sharp cutting edge (Hvorslev, 1949), recommended a maximum 10°, so that the full wall thickness is far removed from the point where the sample enters the tube. Jakobson (1954) investigated the effect of sampler type on the shear strength of clay samples. Samples were collected using nine different types of samplers. These types differ from one another in area ratio, edge angle, inside clearance, drive velocity and other factors. Shear strength of samples were determined by carrying out the unconfined compression tests, the cone test and the laboratory vane test. It was found that an extremely small area ratio offers no special advantages and that the cutting edge taper angle does not seem to have any great influence. However, a very large area ratio or cutting edge taper angle was not recommended. Kallstenius (1958) also studied the effect of area ratio and cutting edge taper angles on the shear strength of Swedish clays. Kallstenius (1958) recommended that a sampler ought to have a sharp edge and a small outside cutting edge angle. Very large OCA has also been not recommended by Jakobson (1954) and Andresen (1981).

The combined requirements for area ratio and cutting edge taper angle to cause low degrees of disturbance were proposed by the International Society for Soil Mechanics and Foundation Engineering's Sub-committee on Problems and Practices of Soil Sampling (1965). For samplers of about 75 mm diameter, they suggested the following combinations of area ratio and cutting edge taper:

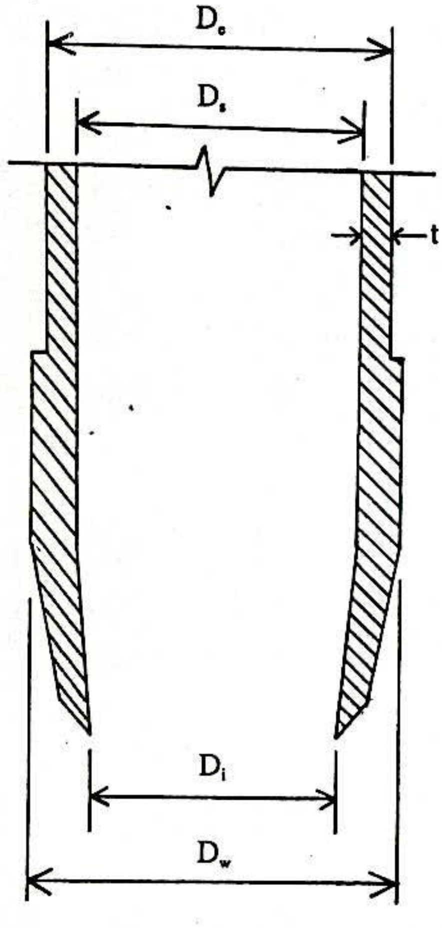


Fig.2.12 Dimensions of a tube sampler

Area Ratio (%)	Outside Cutting Edge Angle (°)
5	15
10	12
20	9
40	5
80	4

Clayton and Siddique (1999) reported that good sampler geometries are available, which are capable of reducing tube sampling strains to acceptably low levels. Siddique and Clayton (1995) reported that the higher the tube sampling strains, the greater is the changes in the undrained soil parameters.

Siddique and Sarker (1996) investigated that reduction up to 41.5%, 35% and 49%, of initial effective stress (σ'_i), undrained strength (s_u) and initial stiffeness (E_i) obtained respectively while increase up to 81% of strain at peak strength (ε_p) yielded due to increase in area ratio from 10.8 to 55.2% for Dhaka clay. Siddique and Sarker (1996) also investigated that reduction up to 36.9%, 32% and 41% of σ'_i, s_u, and E_i provided respectively while increase up to 81% of ε_p obtained due to increase in OCA from 4° to 15° for Dhaka clay. Siddique and Sarker (1996) reported that Skempton's pore pressure parameter, A at peak deviator stress, A_p reduced considerably as area ratio increased and the values of A_p of the "tube" samples collected from different area ratio are negative.

Siddique et al. (2000) also reported that σ'_i, s_u, and E_i, reduced while ε_p increased due to increase in area ratio and OCA for three Chittagong coastal soils. Siddique et al. (2000) also found that A_p reduced considerably due to increase in area ratio and OCA.

The effect of area ratio and outside cutting edge angles (OCA) on soil properties due to tube sampling for the regional clays of Bangladesh are summarised in Table 2.5.

Figs. 2.13 (a) and (b) show the influences of area ratio of samplers on undrained soil parameters for samples of Dhaka clay (Siddique and Sarker, 1996) and a coastal soil (Siddique et al., 2000) respectively. It can be seen from Figs. 2.13 (a) and (b) that strength and stiffnesses decrease with the increase in area ratio while strain at peak strength increases with the increase in area ratio of "tube" samples.

Figs. 2.14 (a) and (b) show the effects of outside cutting edge angles (OCA) of samplers on undrained soil parameters for samples of Dhaka clay and a coastal soil respectively. It can be seen from Figs. 2.14 (a) and (b) that strength and stiffnesses decrease with the increase in OCA while strain at peak strength increases with the increase in OCA of "tube" samples.

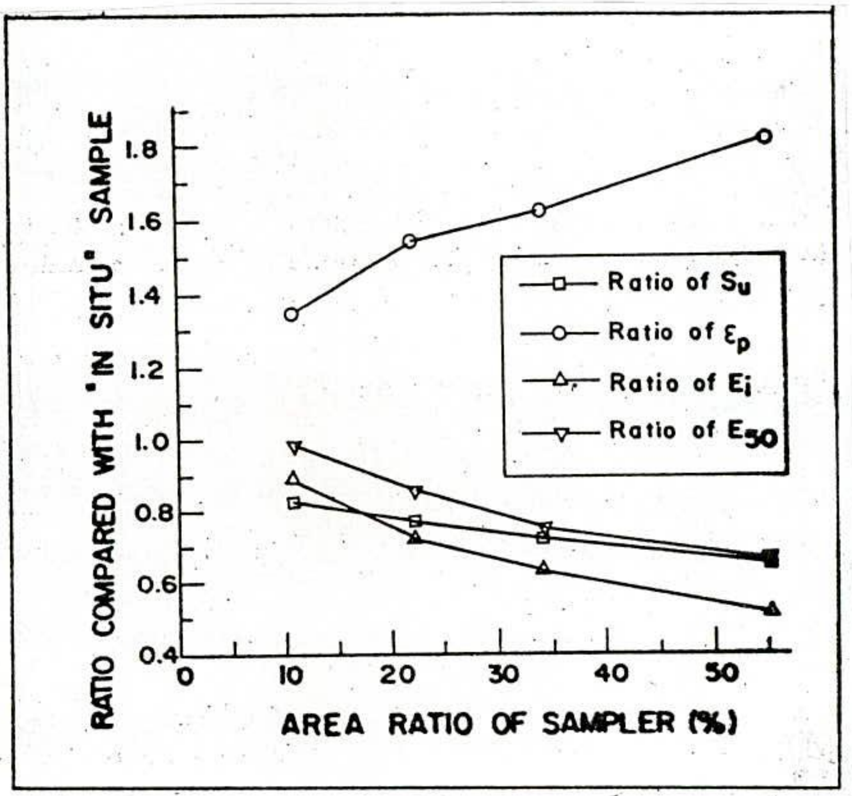
Clayton et al. (1998) conducted a parametric study in order to investigate the influence of the design features on tube sampling disturbance. Reductions in initial mean effective stress, undrained shear strength and secant stiffness have been reported by Clayton et al. (1998) for reconstituted London Clay (LL = 69, PI = 45) due to application of increasing levels of tube sampling strains. Fig. 2.15 shows the plots of axial strain at peak strength versus area ratio of samplers of London clay. It can be seen from Fig. 2.15 that the imposed tube sampling strains were predicted numerically (Clayton et al.1998) and the predicted strain increased with increasing area ratio of the samplers. Fig. 2.16 shows the variation of axial strain at peak strength versus outside cutting edge angle of samplers of London clay. It can be seen from Fig. 2.16 that the predicted strain (Clayton et al.1998) increased with increasing outside cutting edge angle of the samplers.

Clayton et al. (1998) concluded that in order to restrict the disturbance (peak axial strain in compression) to less than 1%, a sampler should have the following values of design parameters:

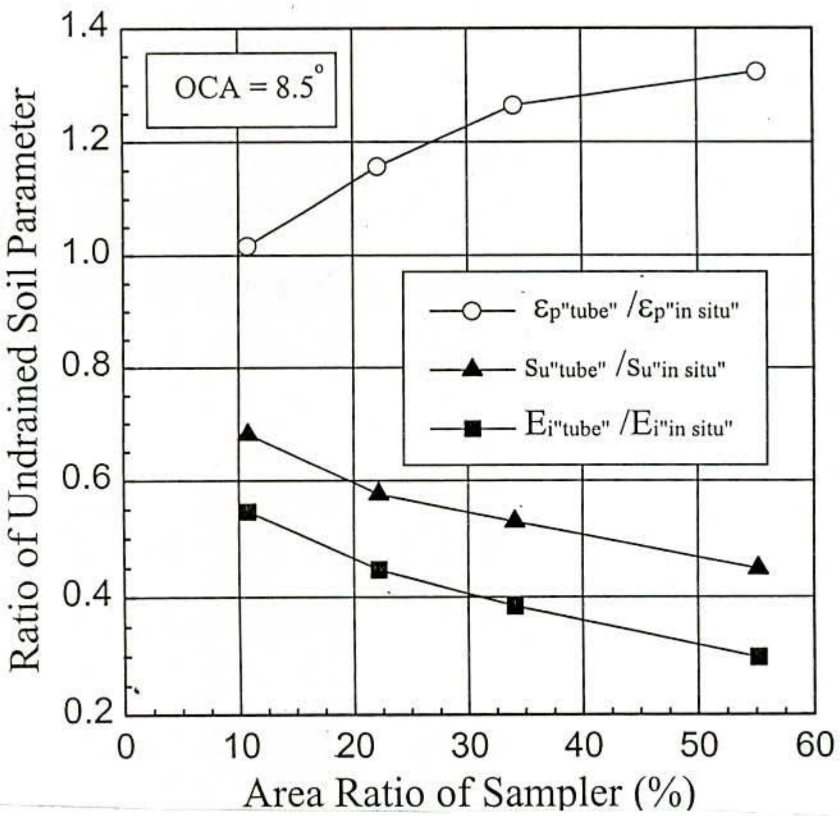
(i) The sampler should have a low area ratio, preferably not more than 10%.

(ii) The sampler should have a moderate inside cutting edge taper angle of 1 to 1.5°.

(iii) The sampler should have a small outside cutting edge taper angle, preferably not more than 5°.

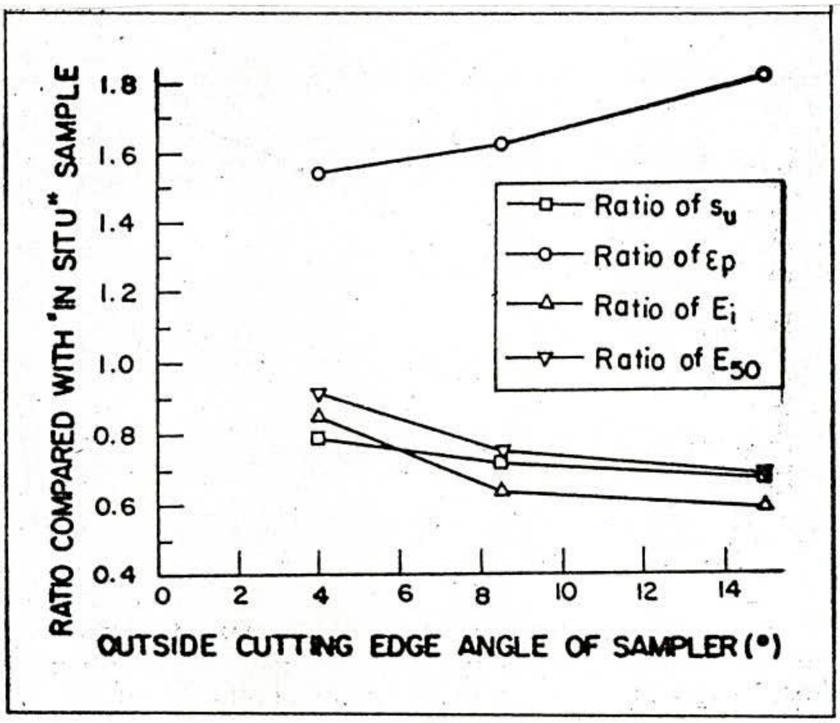


(a)

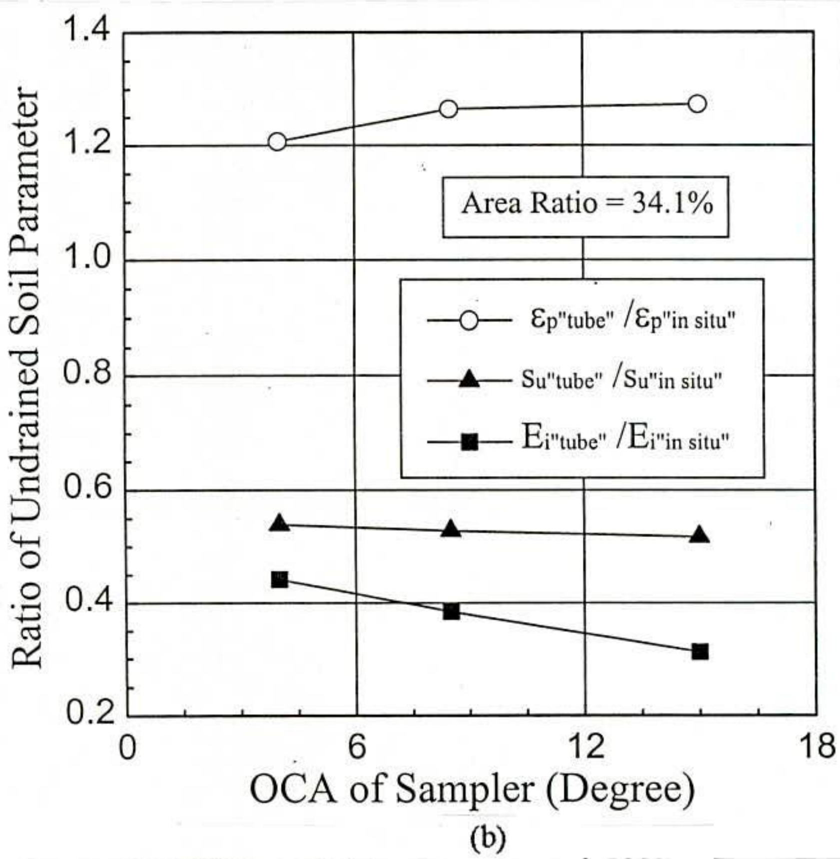


(b)

Fig.2.13 Influence of area ratio of sampler on undrained soil parameters for samples: (a) Dhaka clay (after Siddique and Sarker, 1996), (b) Fakirhat soil (after Siddique et al. 2000).



(a)



(b)

Fig.2.14 Influence of outside cutting edge angle (OCA) of sampler on undrained soil parameters for samples. (a) Dhaka clay (after Siddique and Sarker, 1996), (b) Fakirhat soil (after Siddique et al, 2000).

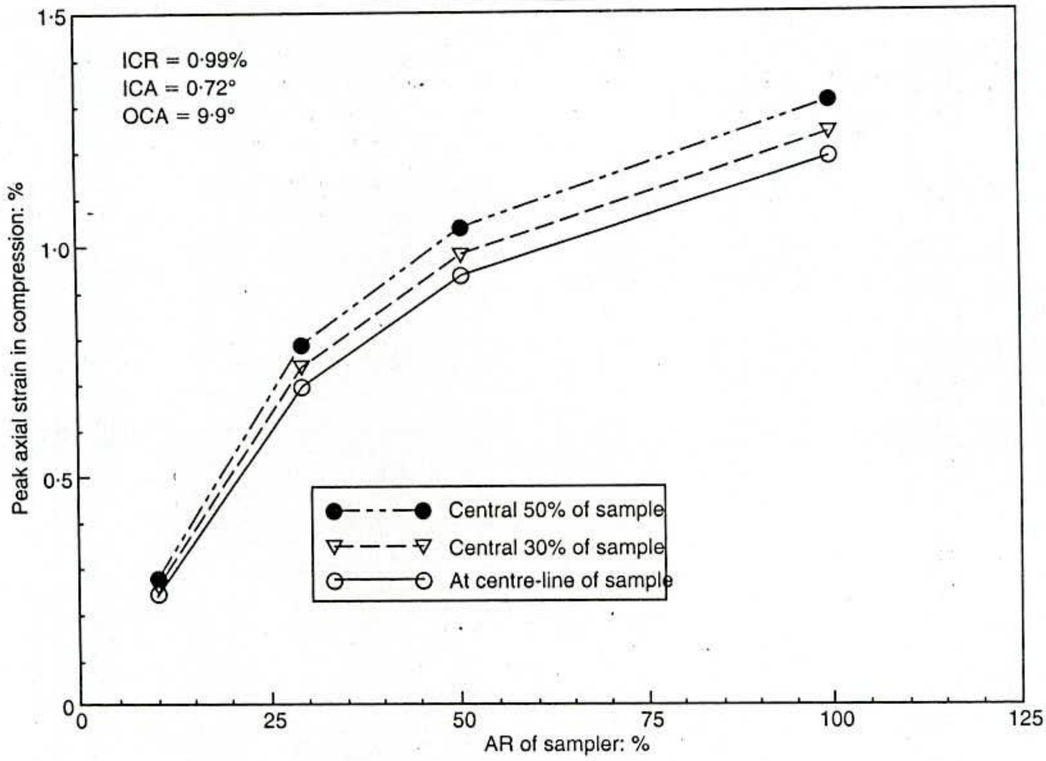


Fig.2.15 Variation of peak axial strain in compression with area ratio of samplers (after Clayton et al, 1998).

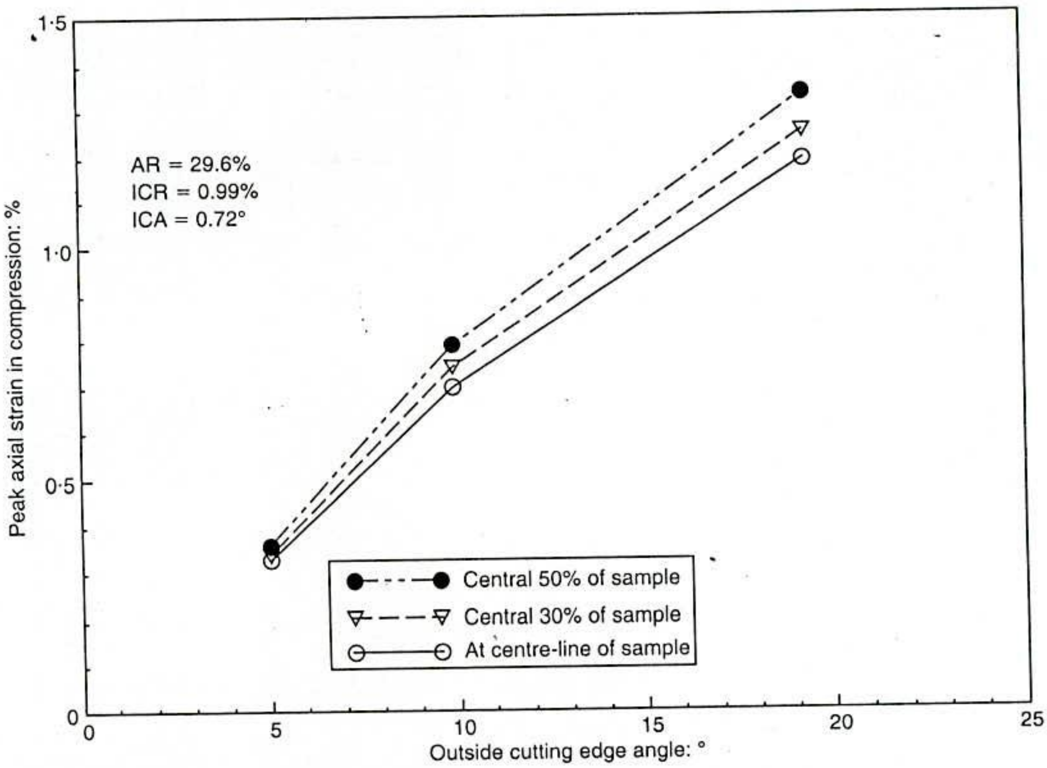


Fig.2.16 Peak axial strain in compression versus outside cutting edge of samplers (after Clayton et al, 1998).

Table 2.5 Effects of tube sampling on soil parameters at various regions of Bangladesh

Location of soil	Sampler Dimensions			%Change in properties compared with "in-situ" sample					Reference
	t mm	AR (%)	OCA (°)	Reduction of σ'_i	Reduction of s_u	Increased of ε_p	Reduction of E_i	Reduction of E_{50}	
Dhaka	1.5	10.8	8.5	18.5	17	35	11	1	Siddique and Sarker (1996)
	3.0	22.2	8.5	26.2	23	54	28	14	
	4.5	34.1	8.5	33.8	28	62	36	25	
	7.0	55.2	8.5	41.5	35	81	49	34	
	4.5	34.1	4	21.5	21	54	15	8	
	4.5	34.1	15	36.9	32	81	41	31	
Patenga	1.5	10.8	8.5	8.3	32	19	34	-	Siddique et al. (2000)
	3.0	22.2	8.5	10.1	38	46	42	-	
	4.5	34.1	8.5	17.3	43	67	50	-	
	7.0	55.2	8.5	33.5	55	78	74	-	
	4.5	34.1	4	13.7	42	62	47	-	
	4.5	34.1	15	23.6	46	70	61	-	
Fakirhat	1.5	10.8	8.5	7.3	34	4	31	-	
	3.0	22.2	8.5	11.8	47	6	42	-	
	4.5	34.1	8.5	16.4	47	26	62	-	
	7.0	55.2	8.5	30.0	55	32	70	-	
	4.5	34.1	4	14.5	46	21	56	-	
	4.5	34.1	15	20.9	48	27	69	-	
Kumira	1.5	10.8	8.5	5.7	34	4	31	-	
	3.0	22.2	8.5	10.0	47	6	42	-	
	4.5	34.1	8.5	12.6	51	8	52	-	
	7.0	55.2	8.5	22.7	56	13	76	-	
	4.5	34.1	4	11.8	50	08	50	-	
	4.5	34.1	15	18.7	51	11	62	-	

2.5.2 EFFECT OF INSIDE AND OUTSIDE CLEARANCE

Inside wall friction is one of the principal causes of disturbance of the sample (Hvorslev, 1949). One of the methods of reducing or eliminating wall friction between the soil and sampler is to provide inside clearance by making the inside diameter of the cutting edge, D_i, slightly smaller than the inside diameter of the sampler tube, D_s, The inside clearance ratio is expressed as follows (Fig. 2.12):

$$Inside\ Clearance\ Ratio = \frac{D_s - D_i}{D_i} \qquad ...(2.2)$$

undesirable than the consequences of adhesion between the soil and the inside of the sampler tube (Clayton et al., 1982). Inside clearance should be large enough to allow partial swelling and lateral stress reduction but it should not allow excessive soil swelling or loss of the sample when withdrawing from the sampling tube. Hvorslev (1949) suggests an inside clearance ratio of 0.75 to 1.5% for long samplers and 0 to 0.5% for very short samplers.

Kallstenius (1958) on the basis of Swedish clays sampled by six different piston samplers, also recommends that a sampler ought to have a moderate inside clearance. The clearance reduces the wall friction and probably counteracts to a certain extent the disturbance from displacement of soil caused by the edge and sampler wall during the driving operation. If the inside clearance and the edge angle are moderate, the above positive effects outweigh the disturbance caused by deformation when the sample tends to fill the clearance. The existence of inside clearance may have detrimental effects on sample disturbance as pointed out by La Rochelle et al (1981). They reported from the work of Sarrailh (1975) that, in general, a "reshaped" 54 mm sampler without inside clearance seemed to give better results than a 54 mm sampler piston tube sampler with inside clearance. The improvement in strength was of the order of 20% or more and the tangent moduli were higher by 50-100%.

Siddique and Clayton (1999) reported that inside clearance of the samplers has an effect on the tube sampling disturbance. Fig. 2.17 shows the variation of axial strain at peak strength in extension versus inside clearance of samplers of London clay. Clayton et al. (1998) reported from Fig. 2.17 that an increase in the inside clearance ratio caused an increase in extensive strain. Clayton et al. (1998) also reported that a slight decrease in compressive strain ahead of the sample tube. Clayton et al. (1998) suggested that in order to restrict the degree of disturbance to less than 1%, a sampler should have a low inside clearance ratio of not more than 0.5%.

In order to reduce outside wall friction, samplers are often provided with outside clearance which is expressed as follows (Fig. 2.12):

$$Outside\ Clearance\ Ratio = \frac{D_w - D_e}{D_e} \qquad ...(2.3)$$

An outside clearance ratio of a few percent may decrease the penetration resistance of samplers in cohesive soils. Although outside clearance increases the area ratio, a clearance of 2 to 3% can be advantageous in clay (Hvorslev, 1949).

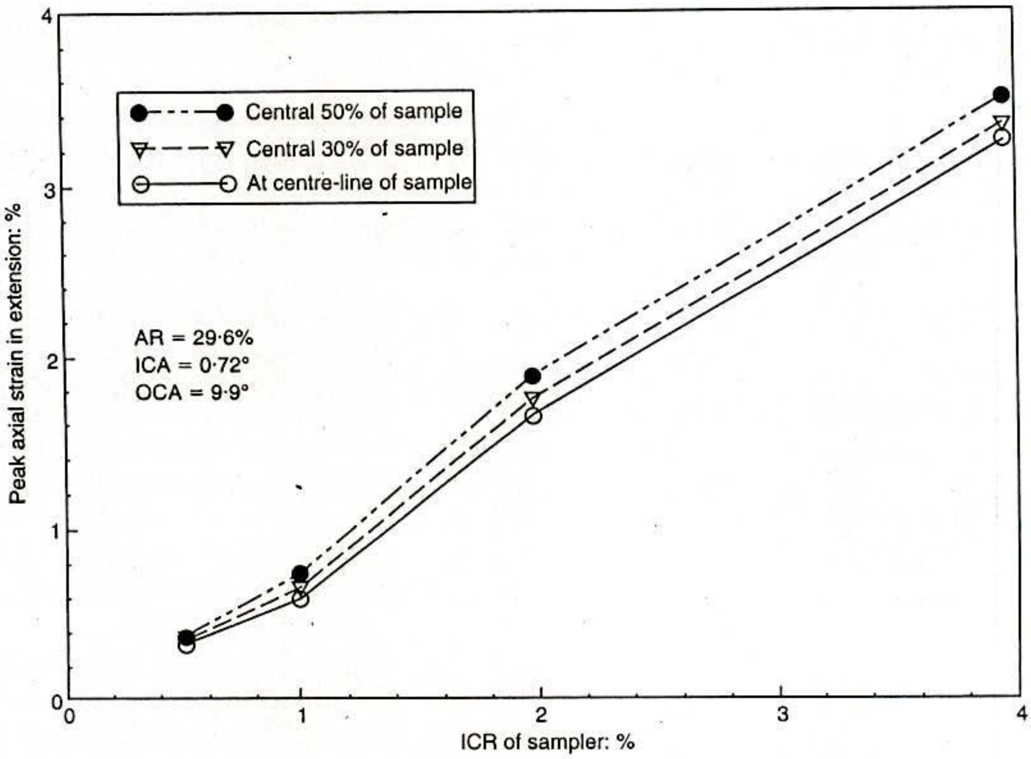


Fig.2.17 Peak axial strain in extension as a function of the inside clearance ratio (ICR) of samplers (after Clayton et al, 1998).

2.6 EFFECT OF SAMPLER DIMENSIONS, SAMPLER TYPES AND SAMPLING METHODS ON SAMPLE DISTURBANCE

A number of workers (Hvorslev, 1949; Berre et al.,1969; Holm and Holtz,1977; Kubba, 1981) have reported the effect of sampler dimensions, particularly diameter and thickness of the sampler tube, upon soil disturbance.

2.6.1 EFFECT OF DIAMETER AND LENGTH

Hvorslev (1949) stated that the amount of disturbance would be decreased with increasing diameter of the sample. Berre et al (1969) observed that larger tube samples, showed more constant behaviour than those from small tube samples. Odometer tests carried out on samples of soft marine clay in Norway indicated that a 95 mm piston sampler (area ratio, AR = 14%, inside clearance ratio, ICR = 1.4%) gave less disturbance than a 54 mm piston sampler (AR = 12%, ICR = 1.3%).

An investigation of the difference in quality of samples taken with large diameter fixed piston samplers and the 50 mm diameter Swedish Standard piston sampler (AR =21%, ICR = 0.4%, outside cutting edge taper angle = 5°) was carried out by Holm and Holtz (1977). The large diameter piston samplers used were the 95 mm NGI (Norwegian Geotechnical Institute) research sampler (AR = 14%, ICR = 1.4%, outside cutting edge taper angle = 10°), the 127 mm Osterberg sampler (AR = 18%, ICR = 0.4%, outside cutting edge taper angle = 7°) and the 124 mm SGI (Swedish Geotechnical Institute) research sampler (AR = 27%, ICR = 1.2% and angle of cutting edge = 5°). The investigation has shown that the results of oedometer tests on 50 mm samples are more scattered, supporting findings of Berre et al (1969). The undrained modulus obtained from 50 mm samples have been found to be lower.

Bozozuk (1971) performed undrained triaxial tests on 1.4 inch diameter samples of soft marine clay. Samples were obtained by the 54 mm NGI piston sampler (AR=11%, ICR = 1%) and the 127 mm Osterberg piston sampler (AR = 6%, ICR = 0.42%). Test results showed that the undrained strengths of samples cut from 127 mm tube sample were higher than those cut from 54 mm tube samples. Samples cut from 54 mm tube samples showed lower stiffness and pore pressure responses.

Sample quality is also related to the length to diameter ratio of the sampler. One of the major factors controlling sample jamming is the length to diameter ratio of the sampler. The optimum length to diameter ratios suggested for clays of different sensitivities are as follows (the Report of the Sub-committee on Problems and Practices in Soil Sampling, 1965).

Sensitivity, S_t	Length to diameter ratio
>30	20
5 to 30	12
<5	10

2.6.2 EFFECT OF DIAMETER TO THICKNESS RATIO (D_e / t RATIO)

Kubba (1981) investigated the effect of thickness of tube on sampling disturbance for a reconstituted Spestone Kaolin (LL = 51, PI = 30). Tube samples were obtained by inserting 38 mm diameter tubes of different walls thickness into a 102 mm diameter "perfect" sample. Three tubes of thickness to diameter ratios of 0.039, 0.072 and 0.105 were used for sampling. Kubba (1981) found that increasing the ratio of wall thickness to diameter of the tube caused a qualitative increase in the degree of disturbance. Kubba (1981) also reported a qualitative increase in the degree of disturbance due to increase in the ratio of thickness to diameter of the samplers.

Marked increase in degree of disturbance (measured in terms of tube sampling strains), with decreasing D_e/t ratio of sampler has also been analytically predicted (Baligh, 1985; Baligh et al., 1987). The levels of straining resulting from penetration of "simple sampler" have been predicted analytically by Baligh et al. (1987). Baligh et al. (1987) found that the peak axial strains are very much dependent on the aspect ratio (D_e/t). Baligh et al. (1987) found from analytical study that the peak axial strain in compression and extension decreases with increasing B/t ratio of the samplers.

Chin (1986) showed that, for thin-walled simple samplers (B/t>>1), both maximum axial strain in compression and extension at the centreline of sampler is approximately given by the following expression;

$$\varepsilon_{max} = 0.385\ (B/t)^{-1} \qquad \ldots(2.4)$$

Clayton and Siddique (1999) reported that both the peak axial strain in compression ahead of the sampler and the maximum axial strain in extension inside the sampler are dependent on the external diameter (B) to thickness (t) ratio of the sampler.

Siddique and Sarker (1996) investigated the effect of D_e/t ratio on undrained soil parameters of reconstituted Dhaka clay by carrying out undrained triaxial compression tests on "tube" samples collected with samplers of varying diameter to thickness (D_e/t) ratio. Siddique and Sarker (1996) reported that strength, stiffnesses and pore pressure parameter decreased while strain at peak strength increased with the decrease in D_e/t ratio of sampler. Siddique et al. (2000) obtained the similar effect of D_e/t ratio on undrained soil parameters for three Chittagong coastal soils.

2.6.3 EFFECT OF SAMPLING METHODS

The influence of sampling methods on some soil properties for two sensitive slightly overconsolidated clays was reported by Milovic (1971). Clay samples were obtained by Shelby tubes and Norwegian piston sampler. The area ratio and inside clearance ratio for both Shelby tube and piston sampler were respectively 12 ± 1.5% and 0.8 ± 0.1%.

Eden (1971) investigated the effect of sampling method on preconsolidation pressure and undrained shear strength for sensitive overconsolidated clay. Sampling was conducted with four types of piston samplers, and the test results were compared with those obtained from block samples. Samplers used were the Swedish soil (Kjellman et al, 1950), the NGI 50 mm, the SGI standard 50 mm, and the 127 mm Osterberg hydraulic sampler. The in-situ strength of the clay was also measured with the field vane test. The results showed that none of the samplers nor the field vane test were successful in obtaining results that could be compared consistently with results obtained from the block samples. The main conclusion of the study is that present methods of sampling of such clays by boring from the surface do not produce satisfactory undisturbed samples in this material.

Raymond et al. (1971) studied the behaviour of sensitive Leda Clay sampled by six different sampling methods to assess the significance of the different features in the design of samplers. Of the five different tube samplers used, the samplers causing least disturbance were, in order:

(i) the 125 mm Osterberg hydraulic piston sampler

(ii) the SGI 50 mm standard piston sampler

(iii) the 50 mm thin-walled Shelby tube piston sampler with sharp outside cutting edge

(iv) the 50 mm thin-walled Shelby tube piston sampler with normal cutting edge, and

(v) the 50 mm thin-walled open-drive Shelby tube.

McManis and Arman (1979) investigated the effect of sampling method on the properties of undisturbed soil specimens. The soil types studied were soft organic silty clays and stiff, fissured Pleistocene clays. Sampling was performed using 76 mm and 127 mm thin-walled open-drive tubes and by hand cutting of block samples. The test results were found to be dependent on the sampler types and type of soil. For stiff fissured clay, the strength of the 76 mm diameter tube sample exceeded that of 127 mm diameter specimen. This was attributed to stress release and migration of moisture toward and along the fissure planes. Maguire (1975) also found that for stiff fissured overconsolidated clay the undrained strength increased with decreasing diameter of sample. However, for soft silty clay, McMains and Arman (1979) found that 127 mm tube specimens exhibited strengths greater than that of 76 mm tube specimens.

Adachi et al (1981) reported that the quality of soil samples was found to depend markedly on the method of boring and sampling. The average undrained shear strengths obtained by percussion borings with the open-drive sampler were almost one-half of those obtained by rotary borings with the fixed piston, thin-walled sampler.

Dietzler et al. (1988) compared the effects of sampling disturbance on shear strength between samples of glacial till (LL = 24, PI = 12) obtained by two method; namely, samples obtained with thin-walled tube sampler (AR = 12%, ICR = 1%), and samples obtained with continuous split-barrel sampler (AR = 89%, ICR = 14%). The comparative laboratory testing program indicated that the continuous sampler may be used to provide soil samples of cohesive fill which are equivalent to those obtained using thin-walled tubes. Test results also showed that the effective shear strength parameters determined using samples obtained by any of the three methods are accurate for use in feasibility or preliminary investigations, especially where the future loading conditions and testing pressures exceed the maximum past confinement.

2.7 ASSESSMENT OF SAMPLE DISTURBANCE

The mechanical properties of soils are modified by sampling disturbance and hence, they can be used to calculate the amount of disturbance quantitatively. The properties of in-situ soils are required as references in calculating disturbance. However, there is no way of obtaining a soil sample so as to maintain exactly the in-situ conditions. This is because its removal involves a change in the in-situ state of stress and usually some disturbance due to sampling and handling. So, degree of disturbance can be estimated by investigating the behaviour of the least disturbed sample.

Because of additional disturbances other than that occurred due to total stress release, the residual effective stress of a disturbed sample, σ'_r is usually less than the effective stress, σ'_{ps} of a "perfect" sample. Perfect sampling, which is usually simulated in the laboratory by consolidating specimens anisotropically in the triaxial apparatus and then releasing firstly the in-situ shear stress and secondly releasing the total isotropic stress to zero under undrained conditions. The isotropic effective stress in a "perfect" saturated sample of clay which had in-situ vertical and horizontal effective stresses of σ_v' and $K_0\sigma_v'$ respectively, is given by the following expression (Ladd and Lambe, 1963):

$$\sigma'_{ps} = \sigma'_v [k_o + A_u(1 - K_o)] \qquad ...(2.5)$$

Where K_0 is the coefficient of earth pressure at rest and A_u is the pore pressure parameter for the undrained release of the in-situ stresses which existed at the K_0-conditions. The parameter A_u for a saturated clay (i.e., Skempton's B parameter is equal to unity) is given by

$$A_u = \frac{\Delta u - \Delta \sigma_h}{\Delta \sigma_v - \Delta \sigma_h} \qquad ...(2.6)$$

Where, Δu is the pore pressure change; and $\Delta\sigma_v$ and $\Delta\sigma_h$ are the changes of vertical and horizontal total stresses.

The residual stress, σ'_r is the initial effective stress because of additional disturbance other than that occurred due to total stress release at the time of "perfect" sampling.

A number of investigators have defined the degree of disturbance (D) in terms of σ'_{ps} and σ'_r. These are as follows:

(a) Ladd and Lambe (1963) proposed that disturbance could be defined by the following expression:

$$\frac{\sigma'_r}{\sigma'_{ps}} \qquad ...(2.7)$$

(b) Noorany and Seed (1965) regarded the difference between σ'_{ps} and σ'_r as a measure of disturbance, i.e.,

$$D = \sigma'_{ps} - \sigma'_r \qquad ...(2.8)$$

(a) Okumura (1971) and Nelson et al (1971) defined the degree of disturbance as follows:

$$D = 1 - \frac{\sigma'_r}{\sigma'_{ps}} \qquad ...(2.9)$$

The degree of disturbance in clays of tube sampling investigated by Siddique and Sarker (1995) and Siddique et al. (2000), at various regions of Bangladesh are shown in Table 2.6. Siddique and Sarker (1996) reported from Table 2.6 that the values of D_d increased from 0.19 to 0.42 due to increase in area ratio from 10.8 to 55.2 (decrease in D_e/t ratio from 40.0 to 10.1) and also the values of D_d increased from 0.22 to 0.37 due to increase in OCA from 4° to 15° for reconstituted Dhaka clay. Siddique et al. (2000) also reported that similar effect of area ratio, OCA and D_e/t ratio on degree of disturbance obtained for reconstituted three coastal soils.

Fig. 2.18 and Fig 2.19 show the variations of degree of Disturbance (D_d) with Area Ratio (AR) and Outside Cutting Angle (OCA) of samplers respectively for Dhaka clay and three Chittagong coastal soils. Siddique and Sarker (1996) and Siddique et al. (2000) explained from Fig. 2.18 and Fig 2.19 that degree of disturbance increased with the increase in area ratio and OCA of sampler respectively.

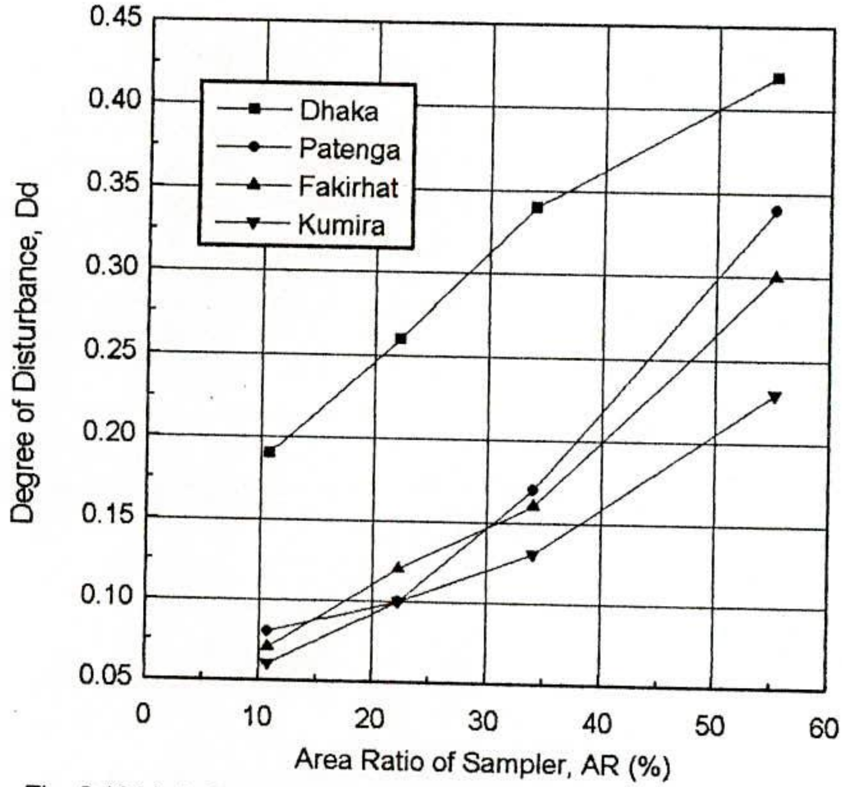


Fig. 2.18 Variation of degree of disturbance with area ratio of sampler for samples (reproduced after siddique and Sarker, 1996; Siddique et al., 2000).

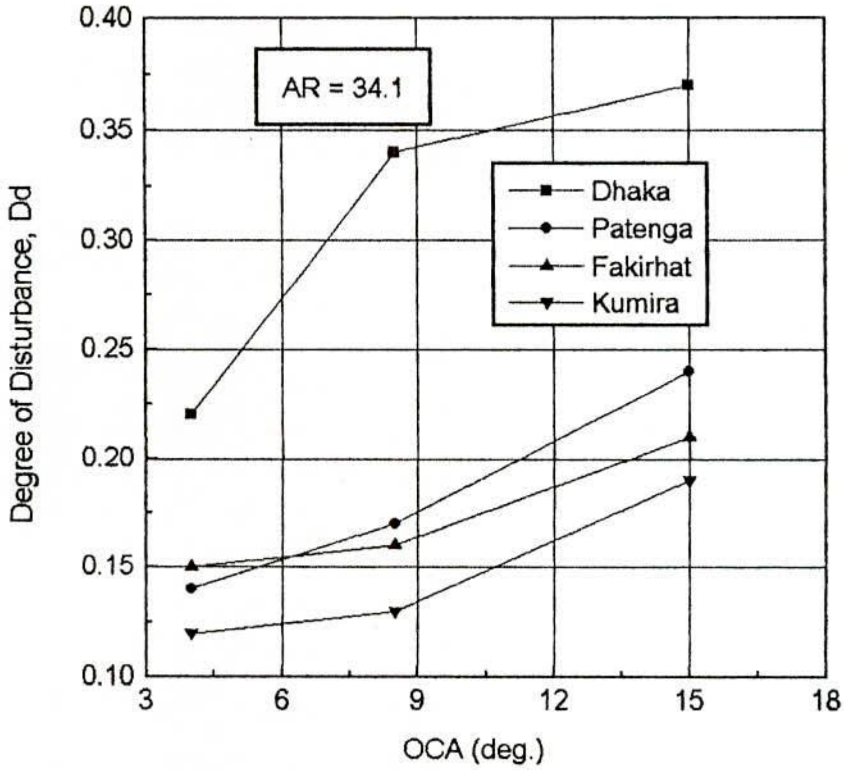


Fig. 2.19 Variation of degree of disturbance with OCA of sampler for samples (reproduced after Siddique and Sarker, 1996; Siddique et al., 2000).

Table 2.6 Quantitative values of Degree of Disturbance for regional soils of Bangladesh

Location of Soil	Tube Sampler Dimensions				Degree of Disturbance	Reference
	t (mm)	AR (%)	OCA (°)	D_e/t ratio		
Dhaka	1.5	10.8	8.5	40.0	0.19	Siddique and Sarker (1996)
	3.0	22.2	8.5	21.0	0.26	
	4.5	34.1	15	14.7	0.37	
	7.0	55.2	8.5	10.1	0.42	
	4.5	34.1	4	14.7	0.22	
	4.5	34.1	15	14.7	0.37	
Patenga	1.5	10.8	8.5	40.0	0.08	Siddique et al. (2000)
	3.0	22.2	8.5	21.0	0.10	
	4.5	34.1	8.5	14.7	0.17	
	7.0	55.2	8.5	10.1	0.34	
	4.5	34.1	4	14.7	0.14	
	4.5	34.1	15	14.7	0.24	
Fakirhat	1.5	10.8	8.5	40.0	0.07	
	3.0	22.2	8.5	21.0	0.12	
	4.5	34.1	8.5	14.7	0.16	
	7.0	55.2	8.5	10.1	0.30	
	4.5	34.1	4	14.7	0.15	
	4.5	34.1	15	14.7	0.21	
Kumira	1.5	10.8	8.5	40.0	0.06	
	3.0	22.2	8.5	21.0	0.10	
	4.5	34.1	8.5	14.7	0.13	
	7.0	55.2	8.5	10.1	0.23	
	4.5	34.1	4	14.7	0.12	

Clayton et al. (1998) from numerical finite element analyses of samples having various area ratio predicted considerable increase in degree of disturbance with increasing area ratio and OCA while decreasing D_e/t ratio. A qualitative increase in the degree of disturbance with increasing area ratio has also been reported by Andresen (1981).

2.8 METHODS USED FOR CORRECTING UNDRAINED STRENGTH OF DISTURBED SAMPLES

Because of sample disturbance, it is necessary to correct the undrained strength in order that is representative of the in situ soil. A number of methods have been proposed for correcting the undrained strength of disturbed sample. Ladd and Lambe (1963) considered the difference between measured residual effective stress, σ'_r and the residual effective stress expected with "perfect" sampling, σ'_{ps} as being similar to an overconsolidation phenomenon which influences the measured strength. For each particular soil they established a relationship between the overconsolidation ratio, OCR and undrained shear strength, s_u. Then by considering the OCR as being equal to σ'_{ps}/σ'_r, they corrected the strength measured at an effective stress of σ'_r to the value that would have existed if the sample had been tested at a stress of σ'_{ps}.

Nelson et al. (1971) also reported the difference between measured residual effective stress, $\sigma'_r(\sigma'_c)$ and the residual effective stress expected with "perfect" sampling, σ'_{ps} (σ'_{cm}) as being similar to an overconsolidation phenomenon which influences the measured strength. Fig. 2.20 shows the effect of OCR on undrained shear strength for various clays. It is found from Fig. 2.20 that undrained shear strength ratio decreases with increasing OCR.

Okumura (1971) proposed a method similar to Ladd and Lambe (1963) to correct for a disturbed measured strength. In order to obtain the base for correction, a triaxial compression test, loaded repeatedly up to failure, is performed on a representative specimen consolidated under K_0-conditions and with its deviator stress released in an undrained condition ("perfect" sample). Test results are plotted as disturbed strength ratio (S_{ur} / S_{up}) against disturbance ratio (σ'_p/σ'_r), where S_{ur} is the undrained strength after each cycle, S_{up} is the undrained strength of the "perfect" sample, σ'_r is the residual effective stress after each cycle and, σ'_p is the residual effective stress of the "perfect" sample and also presents the results from repeated loading simple shear tests plotted as disturbed strength ratio and disturbance ratio. To find out the undisturbed strength of a sample, the residual effective stress of the actual sample is first measured to find its disturbance ratio. The sample is then sheared to find its disturbed strength. The correction curve obtained by the above process gives the perfectly undisturbed strength of each sample.

Siddique et al. (2000) developed a correction curve by plotting disturbed strength ratio (S_{ut} / S_{up}) versus degree of disturbance [1- (σ'_r/σ'_{ps})], where S_{ut} is the undrained strength of the tube sample, S_{up} is the undrained strength of the "perfect" sample, σ'_r is the residual effective stress of the tube sample, and σ'_{ps} is the isotropic effective stress of the "perfect" sample for three coastal soils (Patenga, Kumira and Fakirhat) as shown in Fig. 2.21. This strength correction curve is a wide range of band curves for coastal soil samples. It is found from Fig. 2.21 that undrained shear strength ratio decreases with increasing degree of disturbance.

Tsuchida (1993) has also reported two types of disturbance for unconfined compression strength in soft clay namely, a remolding type disturbance and a crack type disturbance. Tsuchida (1993) recommended that the correction methods proposed by Okumura (1971) and Nelson et. al (1971) are valid only for the remolding type disturbance and not for the crack type disturbance. Tsuchida (1993) also showed that for the crack type disturbance, the reduction in strength obtained from undrained triaxial compression test is much less than that obtained from unconfined compression test.

2.9 METHODS USED FOR MINIMIZING SAMPLE DISTURBANCE EFFECTS

It is possible to reduce the effects of sampling disturbance on the undrained behaviour of clays by reconsolidating the sample to a more appropriate stress level prior to shearing. The following isotropic and anisotropic reconsolidation procedures for minimising the sampling disturbance effects are presented.

2.9.1 ISOTROPIC RECONSOLIDATION

Raymond et al. (1971) applied hydrostatic isotropic consolidation pressures to samples of sensitive Leda clay. The ratio of undrained stiffness to undrained strength was close to undisturbed behaviour, when disturbed samples were consolidated to 50-75% of their preconsolidation pressure. When the consolidation pressures exceeded the preconsolidation pressure, there was a dramatic decrease of the stiffness-strength ratio, indicating a break-down in the structure of the sensitive clay.

Kirkpatrick and Khan (1984) adopted two methods of isotropic reconsolidation to examine whether the "in-situ" undrained behaviour could be reproduced. Hydrostatic reconsolidations to pressures equal to σ_{ps}' and "in-situ" vertical effective pressure, σ_{vc}', were applied to samples of kaolin (PI = 30) and illite (PI = 40). It was found that, reconsolidation to σ_{ps}' resulted in underestimation of "in-situ" strength by as much as 14%. However, hydrostatic reconsolidation to σ_{vc}' had the effect of producing fairly large overestimation of "in-situ" strength of 16% or more. They also reported that the undrained

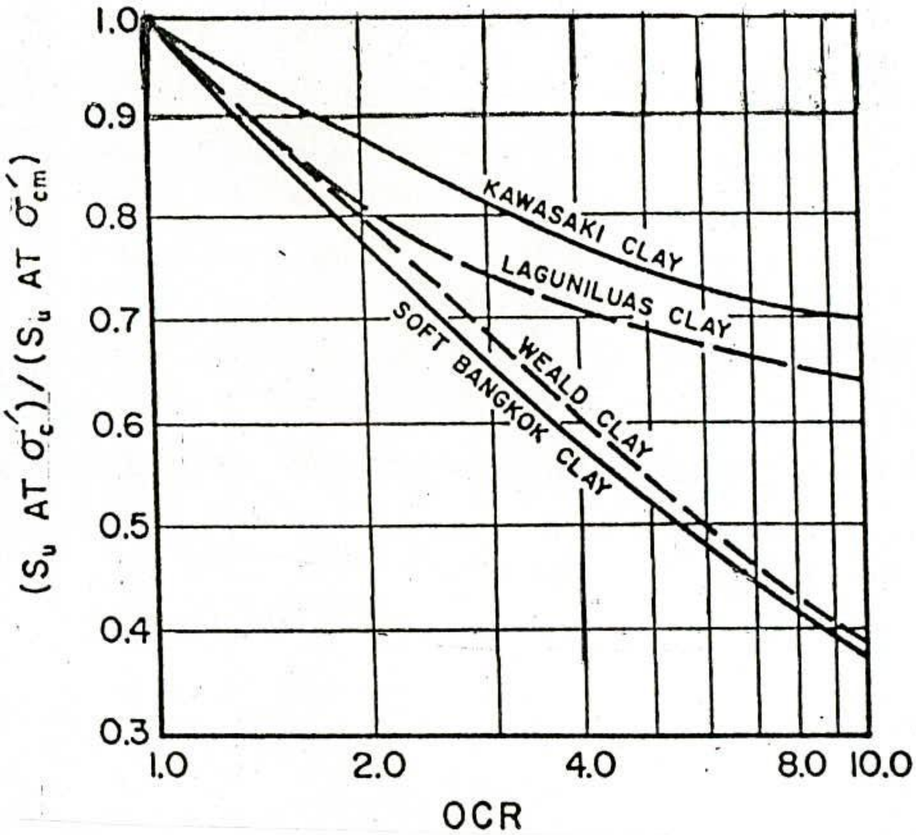


Fig.2.20 Effect of OCR on Undrained strength for various clays (after Nelson et al, 1971).

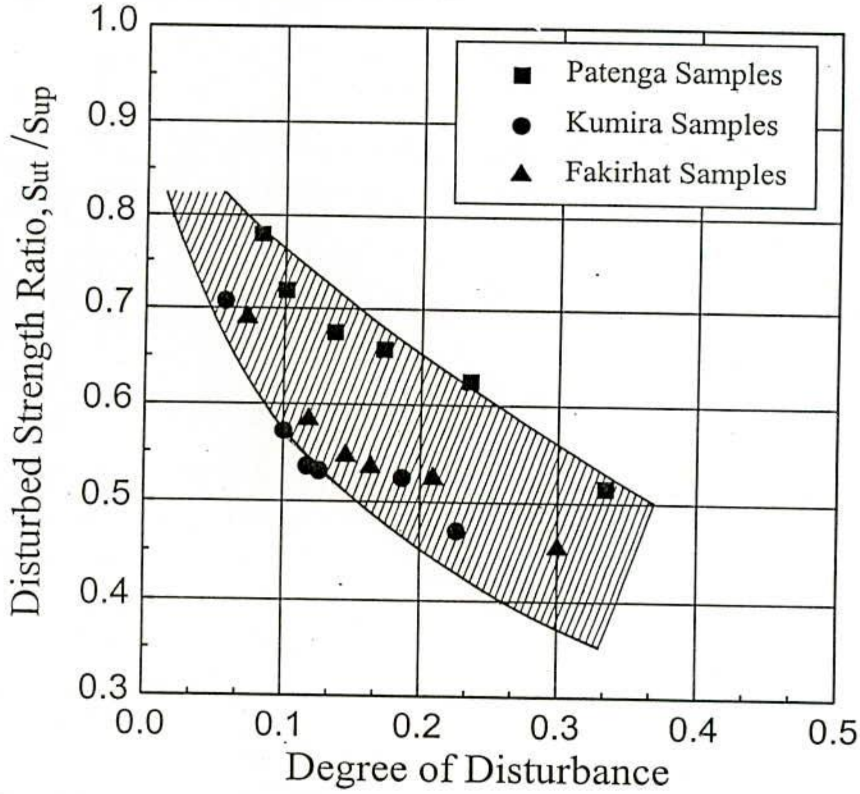


Fig.2.21 Disturbed strength ratio versus degree of disturbance plot for samples of three coastal soils (after Siddique et al, 2000).

strength of the reconsolidated "perfect" samples for normally consolidated Kaolin and Illite clay increase up to 10.7% and 5.77% respectively as compared with those of the "in situ" samples due to isotropic reconsolidation. Failure strains and porewater pressures were heavily overestimated by both the methods of reconsolidation.

Graham et al. (1987) found that in both normally consolidated and overconsolidated samples of kaolin, isotropic reconsolidation to σ_{vc}' overestimated the strength of "in-situ" specimens while isotropic reconsolidation to $0.6\sigma_{vc}'$ underestimated it. In both cases the strains to failure and pore pressure parameter at failure were higher than that of the "in-situ" specimens. These findings agree with those reported by Kirkpatrick and Khan (1984). Similar results have also been reported by Graham and Lau (1988) for normally consolidated kaolin.

2.9.2 ANISOTROPIC RECONSOLIDATION

Anisotropic reconsolidation to in-situ stresses is a preferred method compared with isotropic reconsolidation. K_0-consolidation to the in-situ stresses has been suggested by Davis and Poulos (1967) and Bjerrum (1973). Ladd and Foott (1974) proposed the SHANSEP (Stress History and Normalised Soil Engineering Properties) method for reducing the effects of sample disturbance. This method is based on two concepts. The first is that the soil exhibits normalised stress-strain and strength behaviour. The second is that anisotropic reconsolidation of the soil at 1.5 to 2 times the in-situ vertical effective stress, eliminates the effects of any sample disturbance.

La Rechelle et al (1976) reported that reconsolidation of the samples to the in-situ stresses restored at least part of the strength and stiffness lost by sampling disturbance. However, this effect was negligible in case of good quality samples. Kirkpatrick and Khan (1984) found that compared with the "in-situ" soil, anisotropic reconsolidation to "in-situ" stresses gave a good simulation of strength and stress-strain behaviour and closely similar stress paths. Graham and Lau (1988) also obtained significantly better results for samples reconsolidated to "in-situ" stresses than for samples those were consolidated isotropically. Anisotropic reconsolidation to "in-situ" stresses produced the best overall estimate of strength, porewater pressure parameters and stiffness. Atkinson and Kubba (1981), however, found considerable lower stiffness for anisotropically reconsolidated specimens than that for the "in-situ" specimens, although the normalized effective stress paths were the same for both "perfect" and "in-situ" specimens.

Hight et al. (1985) found from a series of experiments that in the normally consolidated soil the features of the in-situ behaviour were not fully recovered by anisotropic reconsolidation of samples to the in-situ stresses. There were differences in stiffness and post peak behaviour. The effects of a sampling cycle were only fully removed when reconsolidation was continued to vertical effective stress levels greater than 1.75 times the previous maximum vertical stress. This finding is consistent with that on which the SHANSEP approach (Ladd and Foott, 1974) is based. Gens (1982) from his investigation on low plasticity clays reported that anisotropic reconsolidation to approximately 1.8 times the previous maximum vertical stress was required before the effects of sampling and preparation were eliminated.

Baligh et al. (1987) have investigated the effects of reconsolidation on Boston Blue Clay. They found that reconsolidating the soil prior to shear reduced disturbance effects significantly. Reconsolidation according to the SHANSEP method leaded to an undrained (normalized) behaviour that was closer to the "in-situ" soil. They reported that SHANSEP-2.5 gave basically the same results as SHANSEP-1.5, with virtually the same c_u/σ_{vc}' as the "in-situ" soil and overpredicted ε_p by only 45%. Baligh et al. (1987) summarized that most effects of ideal sampling disturbance on the undrained behaviour of K_0-normally consolidated Boston Blue Clay could be reduced by reconsolidating the soil and could, in effect, be virtually eliminated by the SHANSEP method.

2.9.3 ISOTROPIC AND ANISOTROPIC RECONSOLIDATION OF REGIONAL SOILS IN BANGLADESH

Isotropic and anisotropic reconsolidation of "perfect" samples of Dhaka clay and coastal soils in Bangladesh were carried out to investigate the suitability of different reconsolidation procedures to restore while the in-situ behaviour.

Siddique and Farooq (1996) reported that undrained strength ratio (s_u/σ_{vc}') increased by 49% and 70% and stiffness ratio (E_i/σ_{vc}') increased by 42% and 38% due to isotropic reconsolidation for reconstituted normally consolidated "perfect" samples of two coastal soils (Patenga and Kumira, respectively). Siddique and Farooq (1996) also reported that strain at peak strength (ε_p) increased by 56% and 5% while, pore pressure parameter at peak strength (A_p) decreased by 34% and 32% due to isotropic reconsolidation. Siddique and

Farooq (1996) reported that the values of s_u/σ_{vc}' reduced by 13% and 16% (Patenga), 6% and 13% (Kumira), while the values of ε_p increased by 96% and 65% (Patenga), 10% and 2% (Kumira), due to the reconsolidation procedures SHANSEP-1.5 and SHANSEP-2.5, respectively, for 'perfect' samples. Siddique and Farooq (1996) also reported that the values of E_i/σ_{vc}' reduced by 4% and 19% (Patenga), 20% and 38% (Kumira), while the values of A_p increased by 26% and 62% (Patenga), 14% and 34% (Kumira), due to the reconsolidation procedures SHANSEP-1.5 and SHANSEP-2.5 respectively for 'perfect' samples. Siddique and Farooq (1996) found that K_o-reconslidation of "perfect" sample in SHANSEP-1.5σ'_{vc} produced the best agreement between the "perfect" and "in situ" samples in terms of undrained strength ratio, stiffness ratio and A_p-values for two coastal soils.

Siddique et al. (1997) reported that the value of s_u/σ_{vc}' increased by18%, 19% and 21% and E_i/σ_{vc}' increased by 40%, 43% and 60% due to isotropic reconsolidation for reconstituted normally consolidated "perfect" samples of three coastal soils. Siddique et al. (1997) reported that ε_p increased by 61%, 54% and 50% and A_p increased by 7%, 7% and 7% due to isotropic reconsolidation. Siddique et al. (1997) also reported that the values of s_u/σ_{vc}' and E_i/σ_{vc}' reduced while the values of ε_p and A_p increased due to the reconsolidation procedures CKoU-1.0σ'_{vc}, SHANSEP-1.5σ'_{vc} and SHANSEP-2.5σ'_{vc} for 'perfect' samples of three coastal soils as compared with those of the "in situ" samples. Siddique et, al. (1997) reported that reconsolidation using Bjerrum procedure (CK_OU-1.0 σ'_{vc}) agreed more closely with "in situ" samples for 'perfect' samples of three coastal soils.

Siddique and Sarker (1998) reported that the values of s_u/σ_{vc}' and E_i/σ_{vc}' increased by 26% and 139% respectively due to isotropic reconsolidation for reconstituted normally consolidated "perfect" samples of Dhaka clay . Siddique and Sarker (1998) also reported that the value of ε_p increased by 62% while, A_p decreased by 26% due to isotropic reconsolidation. Siddique and Sarker (1998) reported that the values of s_u/σ_{vc}' reduced by 21% and 15% while the values of ε_p increased by 62% and 81% due to the procedures SHANSEP-1.5 and SHANSEP-2.5, respectively, for 'perfect' samples of Dhaka clay. Siddique and Sarker (1998) also reported that the values of E_i/σ_{vc}' reduced by 26% and 54% while the values of A_p increased by 39% and 55% due to the procedures SHANSEP-1.5 and SHANSEP-2.5 respectively for 'perfect' samples. Siddique and Sarker (1998) found that reconsolidation of "perfect" specimens using SHANSEP procedures could not restore the characteristics of the "in situ" specimen in terms of its strength, strain, stiffness and pore pressure response for normally consolidated Dhaka clay.

A comparison of undrained shear characteristies of "perfect" samples due to isotropic and anisotropic reconsolidation of regoinal soils of Bangladesh is shown in Table 2.7.

Fig. 2.22 shows a comparison of variations of deviator stress with axial strain of "in situ" and reconsolidated "perfect" samples of Dhaka clay. Siddique and Sarker (1998) explained from Fig. 2.22 that strengths due to isotropic and anisotropic reconsolidations of "perfect" samples are greater than that of "in situ" sample.

Table 2.7. Comparison of Undrained Shear Characteristies of "In-situ" and Reconsolided "Perfect" Samples of Regoinal Soils of Bangladesh.

Location	Test Type	S_u / σ'_{vc}	ε_p (%)	E_i / σ'_{vc}	A_p	Reference
Dhaka	CIU- 1.0 σ'_{vc}	0.49	6.0	460	0.76	Siddique and Sarker (1998)
	SHANSEP-1.5	0.31	6.0	141	1.43	
	SHANSEP-2.5	0.33	6.7	88.4	1.60	
	In Situ Sample	0.39	3.7	192	1.03	
Patengha	CIU- 1.0 p_0'	0.67	13.1	255.9	0.43	Siddique and Farooq (1996)
	SHANSEP-1.5	0.39	16.5	173.9	0.82	
	SHANSEP-2.5	0.38	13.9	145.8	1.05	
	In Situ Sample	0.45	8.4	180.3	0.65	
Kumira	CIU- 1.0 p_0'	0.80	14.8	306.3	0.40	
	SHANSEP-1.5	0.44	15.5	176.7	0.51	
	SHANSEP-2.5	0.41	13.9	136.6	0.79	
	In Situ Sample	0.47	14.1 .	221.2	0.59	
Banskhali	CIU – 1.0 σ'_{vc}	0.40	11.3	230.0	0.81	Siddique et al. (1997)
	CkoU- 1.0 σ'_{vc}	0.336	7.5	156.1	0.74	
	SHANSEP- 1.5	0.305	9.8	123.8	1.31	
	SHANSEP- 2.5	0.293	10.5	103.1	1.40	
	In Situ Sample	0.34	7.0	163.8	0.76	
Anwara	CIU- 1.0 σ'_{vc}	0.424	12.0	250.0	0.79	
	CkoU- 1.0 σ'_{vc}	0.346	8.3	170.7	0.72	
	SHANSEP- 1.5	0.32	10.6	132.0	1.20	
	SHANSEP- 2.5	0.31	12.2	109.9	1.32	
	In Situ Sample	0.357	7.8	175.2	0.74	
Chadanaish	CIU-1.0 σ'_{vc}	0.447	13.2	295.0	0.76	
	CkoU- 1.0 σ'_{vc}	0.364	9.3	173.0	0.73	
	SHANSEP- 1.5	0.327	11.2	140.0	1.27	
	SHANSEP- 2.5	0.32	11.6	112	1.38	
	In Situ Sample	0.37	8.8	184	0.71	

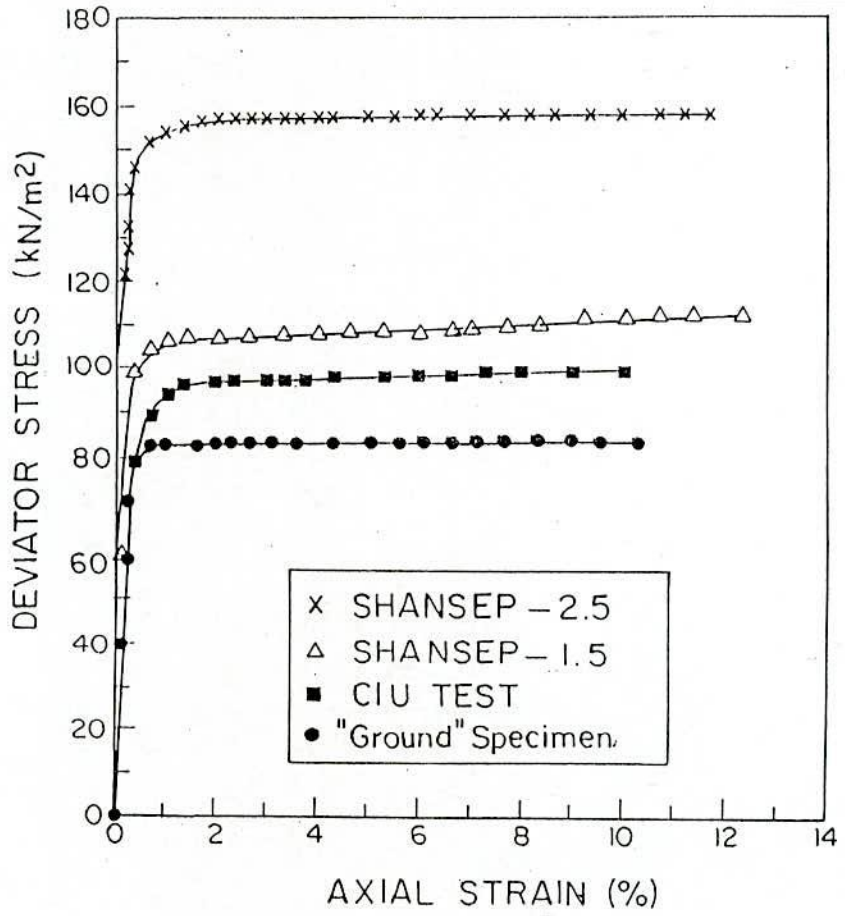


Fig.2.22 Deviator stress versus axial strain plots for "in situ" and reconsolidated "perfect" samples for normally consolidated Dhaka clay (after Siddique and Sarker, 1998).

Fig. 2.23 shows the plots of normalised deviator stress versus axial strain of "in situ" and reconsolidated "perfect" samples of a coastal soil. Bashar et al. (1997b) reported from Fig. 2.23 that normalised strength of reconsolidated "perfect" samples using Bjerrum procedure (CK_OU-1.0 σ'_{vc}) agreed more closely with that of "in situ" samples than other reconsolidation procedures.

Fig.2.24 shows the variation of pore pressure parameter, A with axial strain of "in situ" and reconsolidated "perfect" samples of a coastal soil. Bashar et al. (1997b) reported from Fig. 2.24 that values of A for reconsolidated "perfect" samples using Bjerrum procedure (CK_OU-1.0 σ'_{vc}) produced better agreement with that of "in situ" samples than other reconsolidation procedures.

Isotropic and anisotropic reconsolidation of "tube" samples of Dhaka clay and coastal soils in Bangladesh were carried out to investigate the suitability of different reconsolidation procedures to restore while the in-situ behaviour. A comparison of undrained shear properties of "tube" samples due to isotropic and anisotropic reconsolidation of regoinal soils in Bangladesh is shown in Table 2.8.

Sarker (1994) reported that the values of s_u/σ_{vc}' and E_i/σ_{vc}' decreased by 8% and 31% due to isotropic reconsolidation for reconstituted normally consolidated "tube" samples of Dhaka clay . Sarker (1994) reported that the value of ε_p increased by 27% while, the value of A_p reduced by 2% due to isotropic reconsolidation. Sarker (1994) also found that the values of s_u/σ_{vc}' reduced by 21% and 18% while the values of ε_p increased by 62% and 81% due to the reconsolidation procedures SHANSEP-1.5 and SHANSEP-2.5 respectively for 'tube' samples of Dhaka clay. Sarker (1994) also reported that the values of E_i/σ_{vc}' reduced by 27% and 56% while the values of A_p increased by 16% and 61% due to the procedures SHANSEP-1.5 and SHANSEP-2.5 respectively. Sarker (1994) concluded that K_o-reconsolidation of the "tube" samples beyond in situ stresses could not recover the "in situ" behaviour and the result of K_o-reconsolidation of "tube" samples using the SHANSEP procedures of reconsolidation to restore "in situ" behaviour may not be applicable to Dhaka clay samples.

A comparison of variations of normalised deviator stress with axial strain of "in situ" and reconsolidated "tube" samples of Patenga clay is shown in Fig. 2.25. Farooq (1995) reported from Fig. 2.25 that normalised strengths due to reconsolidation using SHANSEP-1.5 and

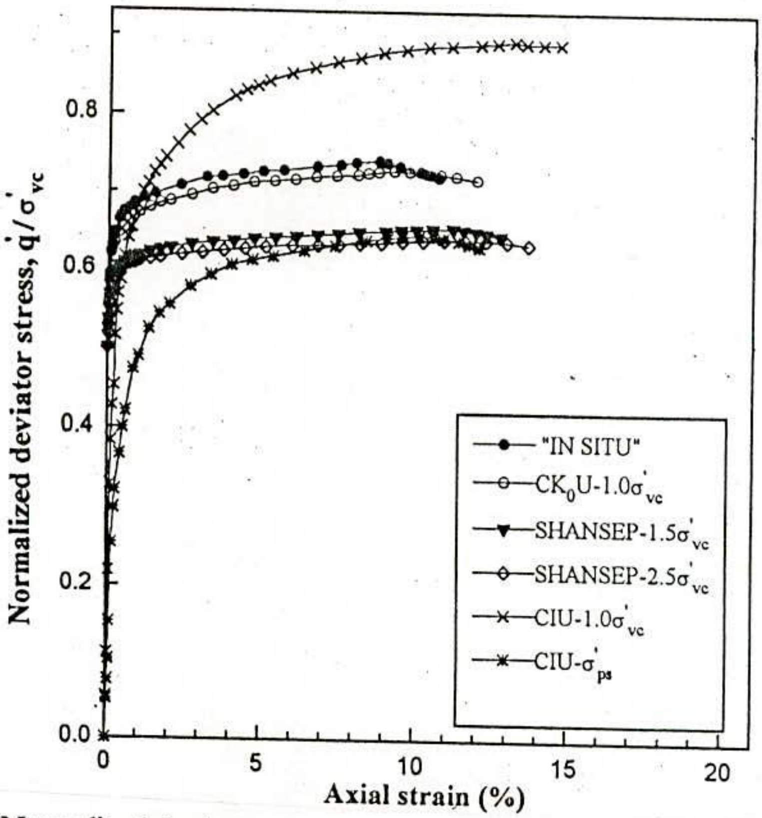


Fig.2.23 Normalized deviator stress versus axial strain plots for "in situ" and reconsolidated "perfect" samples for a normally consolidated coastal soil (after Bashar et al., 1997b).

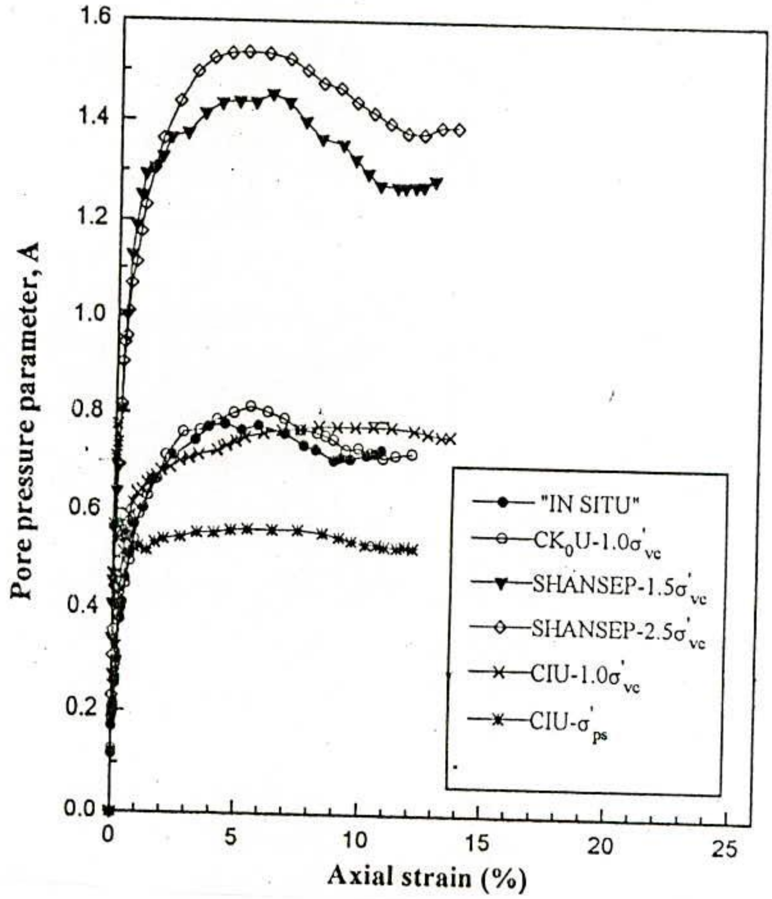


Fig.2.24 Pore pressure parameter, A versus axial strain plots for "in situ" and reconsolidated "perfect" samples for a normally consolidated coastal soil (after Bashar et al., 1997b)

SHANSEP-2.5 procedures are lower while, normalised strength due to isotropic reconsolidation is greater of "tube" samples than that of "in situ" sample.

Table 2.8. Comparison of Undrained Shear Properties of "In-situ" and Reconsolidated "Tube" Samples at Various Regions of Bangladesh.

Location	Test Type	S_u / σ'_{vc}	ε_p (%)	E_i / σ'_{vc}	A_p	Reference
Dhaka	CIU- 1.0 σ'_{vc}	0.36	4.7	132.8	1.01	Sarker (1994)
	SHANSEP-1.5	0.31	6.0	139.3	1.16	
	SHANSEP-2.5	0.32	6.7	84.0	1.66	
	In Situ Sample	0.39	3.7	192	1.03	
Patengha	CIU- 1.0 p_0'	0.60	14.4	218.7	0.49	Siddique et al. (2000)
	SHANSEP-1.5	0.41	14.1	160.8	0.56	
	SHANSEP-2.5	0.43	16.6	158.0	0.56	
	In Situ Sample	0.45	8.4	180.3	0.65	
Kumira	CIU- 1.0 p_0'	0.81	13.4	247.1	0.17	
	SHANSEP-1.5	0.47	17.9	173.5	0.28	
	SHANSEP-2.5	0.48	14.3	167.5	0.46	
	In Situ Sample	0.47	14.1	221.2	0.59	

The variation of pore pressure change with axial strain of "in situ" and reconsolidated "tube" samples of Patenga, is shown in Fig. 2.26. Farooq (1995) reported from Fig. 2.26 that pore pressure changes due to isotropic, SHANSEP-1.5 and SHANSEP-2.5 reconsolidation procedures of "tube" samples are greater than that of "in situ" sample.

Siddique et al. (2000) reported that the values of s_u/σ_{vc}', E_i/σ_{vc}' and ε_p increased while A_p decreased due to isotropic reconsolidation for reconstituted normally consolidated "tube" samples of two coastal soils (Patenga and Kumira). Siddique et al. (2000) also reported that the values of s_u/σ_{vc}', E_i/σ_{vc}' and A_p reduced while the values of ε_p increased due to the reconsolidation using SHANSEP-1.5 and SHANSEP-2.5 procedures for 'tube' samples.
Siddique et, al. (2000) conclued that reconsolidation of "tube" samples using SHANSEP-1.5σ'_{vc} procedure produced better agreement with the properties of the respective "in situ" samples for reconstituted normally consolidated two coastal soils.

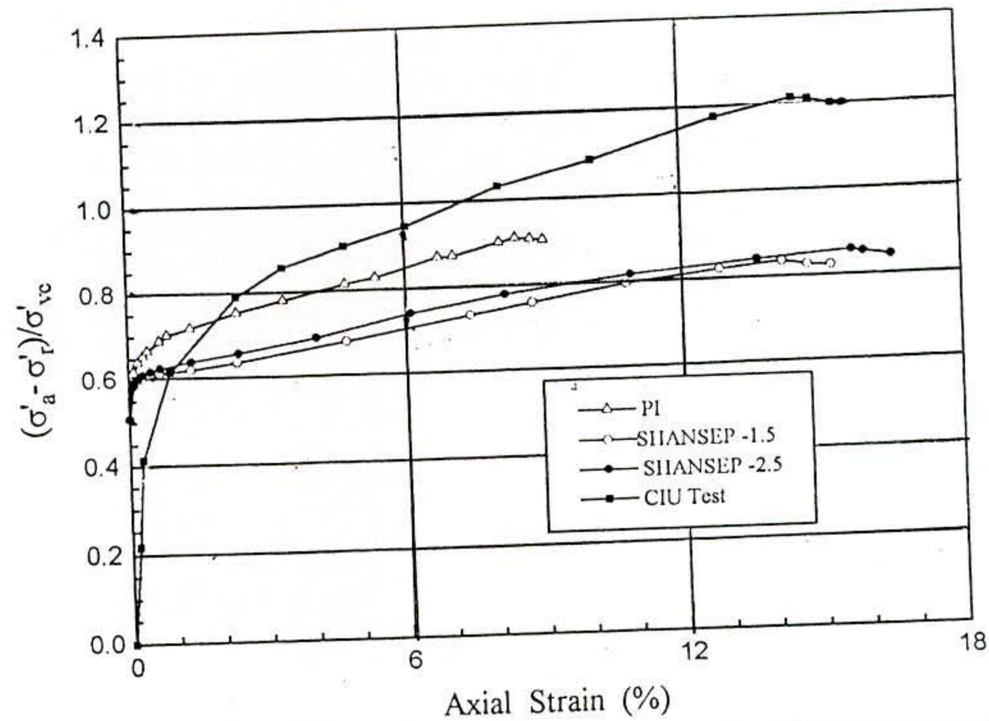


Fig.2.25 Normalized deviator stress versus axial strain plots for "in situ" and reconsolidated "tube" samples for a normally consolidated coastal soil (after Farooq, 1995).

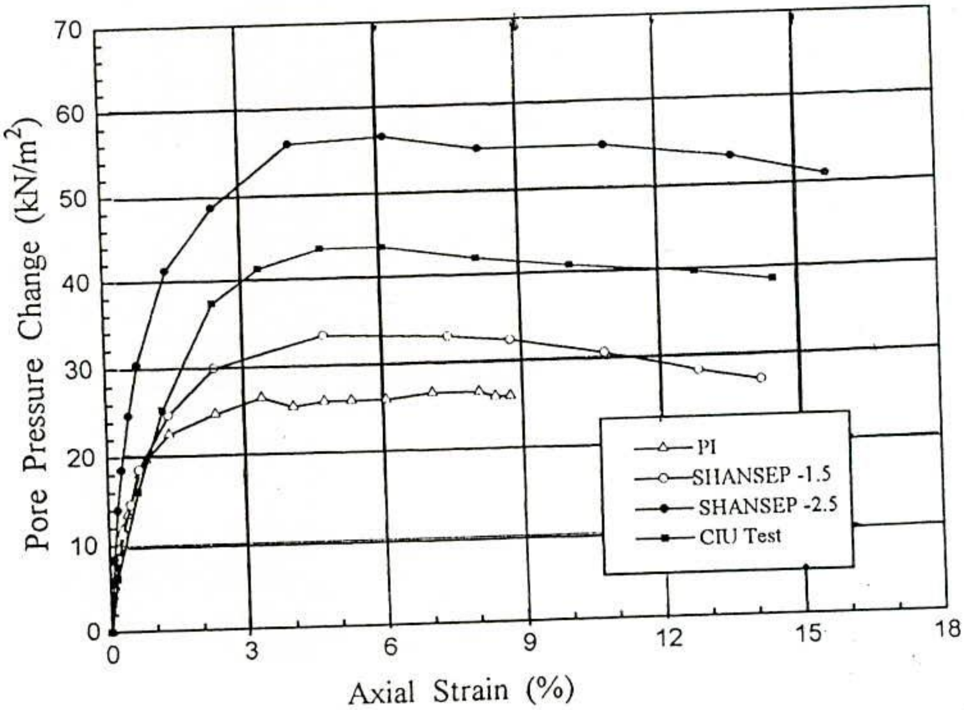


Fig.2.26 Pore pressure Change versus axial strain plots for "in situ" and reconsolidated "tube" samples for a normally consolidated coastal soil (after Farooq, 1995).

CHAPTER 3

EQUIPMENT AND INSTRUMENTATION

3.1 GENERAL

To investigate the sampling disturbance in overconsolidated Dhaka clay, "perfect" samples, "in-situ" samples and "tube" samples were prepared from reconstituted Dhaka clay. A number of instruments and equipment have been used for performing the tests required in this investigation. This chapter describes the principal equipment and instruments used for this research.

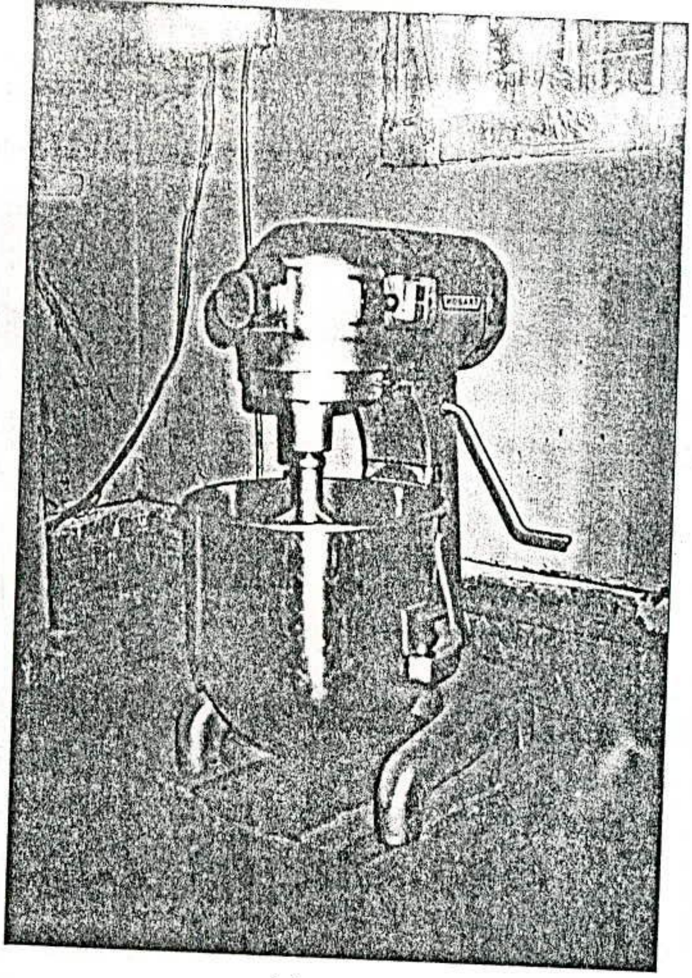
3.2 EQUIPMENT USED

For the preparation of soil slurry, a rotary mixer was used. In order to consolidate the soil slurry under K_0-condition, a large consolidation cell was used.

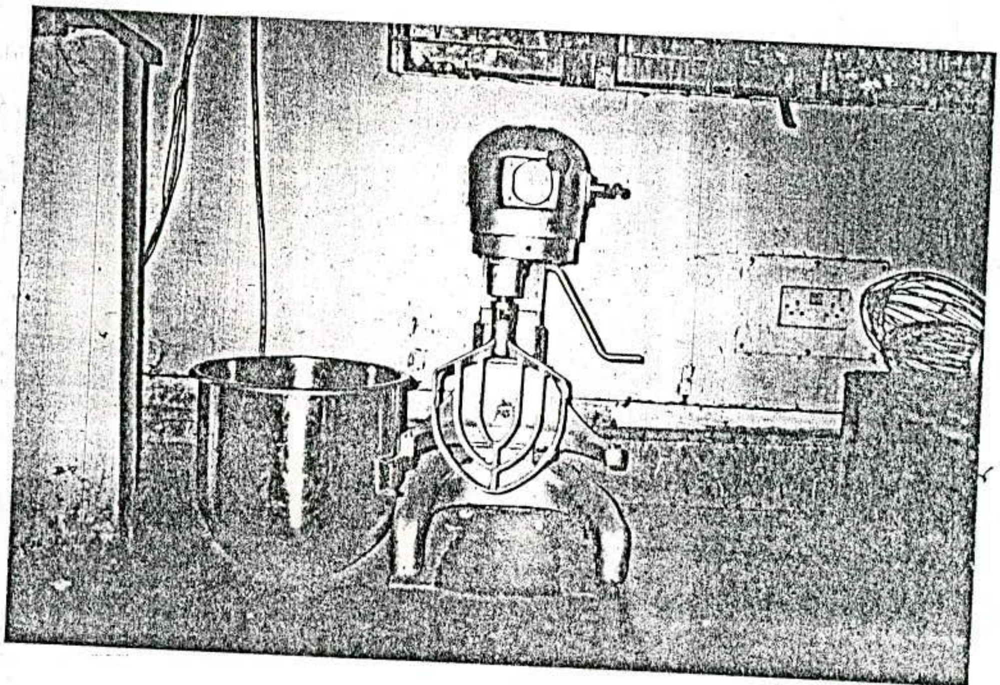
Triaxial apparatus along with volume change and pore pressure measuring devices was used to determine the undrained shear strength, stress-strain and pore pressure characteristics of "perfect", "in situ" and "tube" samples.

3.2.1 THE ROTARY LABORATORY MIXER

A Hobart mixer machine was used for making soil slurry. The rotary blades of this machine ensured proper mixing of soil particles with water over a short period of time at the required moisture content. The mixer machine used has a dimension of 738 mm x 406 mm x 489 mm and includes a three speed gear box driven by a fully enclosed and ventilated motor. The shift handle is mechanically interlocked with the switch, giving definite gear location and making necessary to switch off the motor before changing gear and the beater shaft is carried on ball bearings. The bowl locks at the top and bottom of lift travel, which is controlled by convenient hand lever. The speed used for preparing slurry was 113 revolutions/min for attachment and 198 revolutions/min for beater. The mixing time was approximately 30 minutes. A photograph of the rotary mixer machine is shown in Fig. 3.1(a), and Fig. 3.1(b) shows the photograph of the attachment and bowl of the mixer machine.



(a)



(b)

Fig.3.1 Hobert laboratory mixer machine: (a) Photograph of the machine, (b) Photograph of attachment and bowl

3.2.2 APPARATUS FOR K_0-CONSOLIDATION OF SLURRY

The apparatus consists of a large consolidation cell (260 mm internal diameter and 305 mm high) with loading frame arrangements. A photograph of the apparatus is shown in Fig. 3.2. The K_0-consolidation cell containing the soil slurry is placed on a rigid platform. The platform is raised manually by rotating a wheel and thus loading the soil sample through a loading ram and proving ring. In this process, continuous raising of platform by manual operation is required to adjust with the deformation i.e. to maintain required pressure on the sample. The deformation of the proving ring is measured by a dial gauge that gives the load imposed at any time.

3.2.3 TRIAXIAL APPARATUS

Triaxial apparatus was used for compression test under undrained condition. A 38 mm typical Soil test triaxial machine was used for compression test. The cell had the facility of drainage through both top and bottom of the sample. The cell is provided with a motorised drive unit. The rate of strain during undrained shear test can be controlled by selecting proper driver and driven numbers and gear position. Deformation rates between 0.00064 mm/min and 1.50 mm/min can be applied to sample. A schematic diagram of the triaxial cell is shown in Fig. 3.3. In the triaxial cell, A standard proving ring of 2.8 kN capacity having resolution of 1.8N was used to measure the axial load. Axial deformations during consolidation and shearing of the samples were measured by a 25-mm strain gauge having resolution of 0.0254 mm.

Cell pressure to sample was applied using a standard pressure gauge of operating range from 0 to 1700 kN/m^2. Back pressure was applied to sample using dash pot and control cylinder system. Back pressure up to 1200 kN/m^2 can be applied which is monitored by standard Budenberg test gauge. Fig. 3.4 (a) and (b) shows dash pot and control system and volume change measurement device respectively attached with triaxial machine.

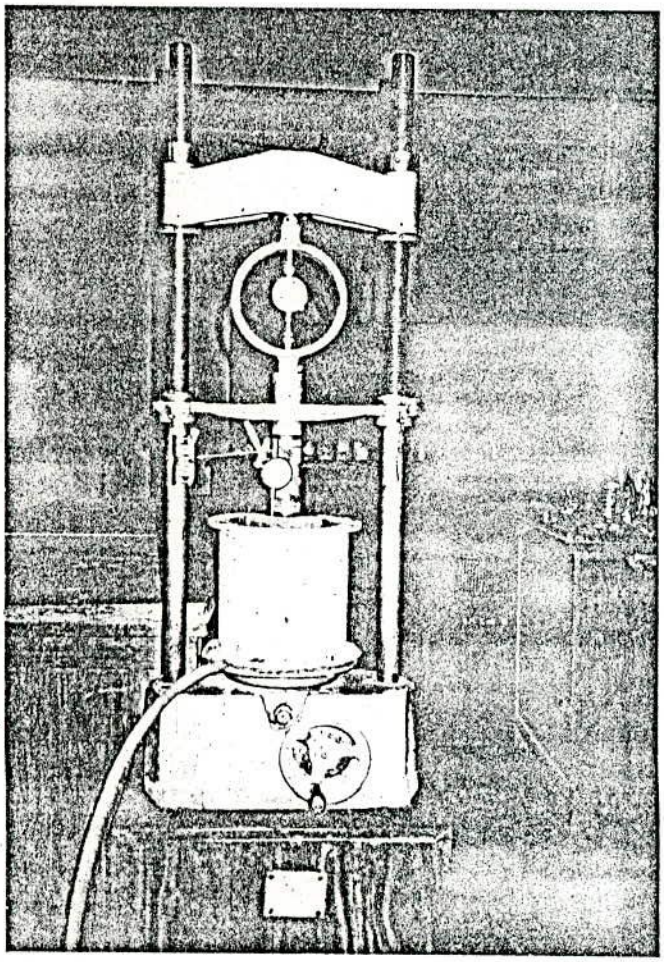


Fig. 3.2 Apparatus for K_o-consolidation of soil slurry

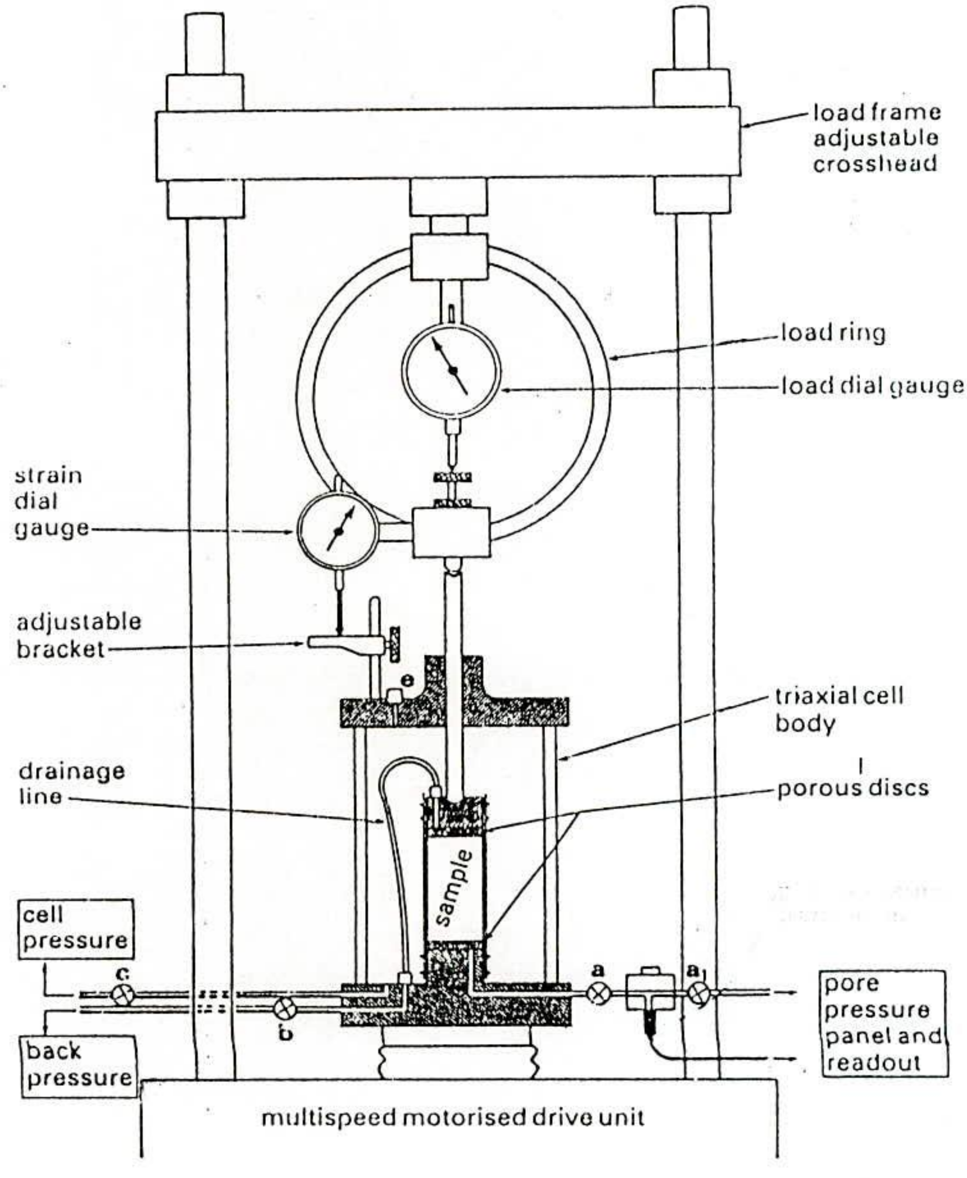


Fig. 3.3 A schematic diagram of triaxial cell

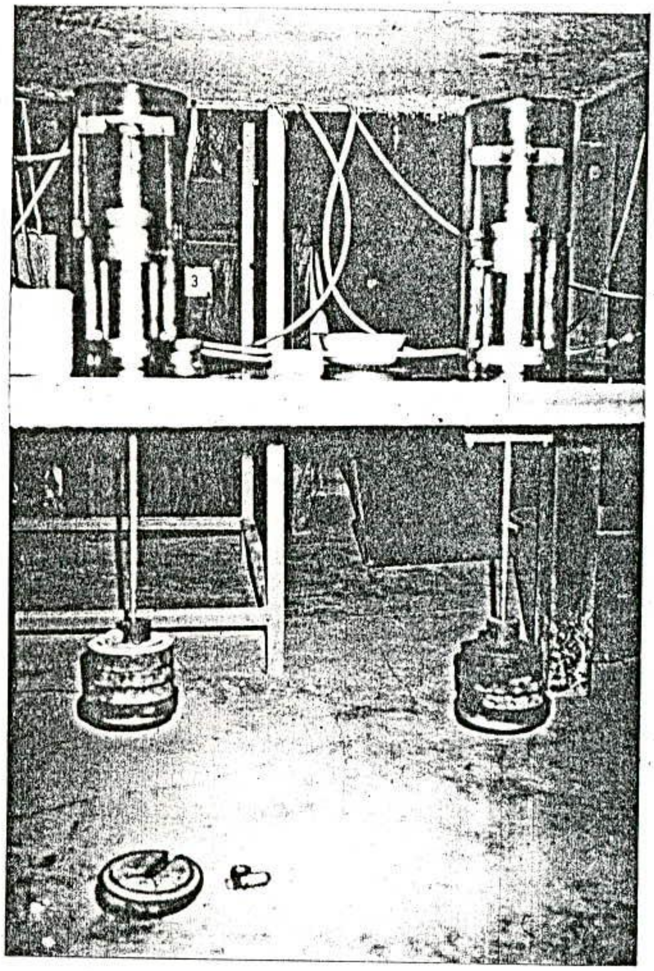
3.2.4 VOLUME CHANGE MEASUREMENT DEVICE

Three methods can be applied to measure the volume change in triaxial testing (Bishop and Henkel, 1962). The first method measures the volume of fluid entering or leaving the triaxial cell to compensate for the change in volume of the sample. This method is used for the partially saturated soils. Appropriate corrections are required for cell and tubing expansion and piston rod penetration into the chamber during shearing. The second method measures the volume of fluid entering or leaving the pore space of the soil. This method is used only for saturated specimens. The third permits calculation of volume from direct measurement of the change in length and diameter of the specimen using local axial and radial strain measuring devices (Clayton and Khatrush, 1986; Clayton et al., 1989; Hoque et al., 1996 and 1997; Jardine et al., 1984). This method may be used for both saturated and unsaturated specimens.

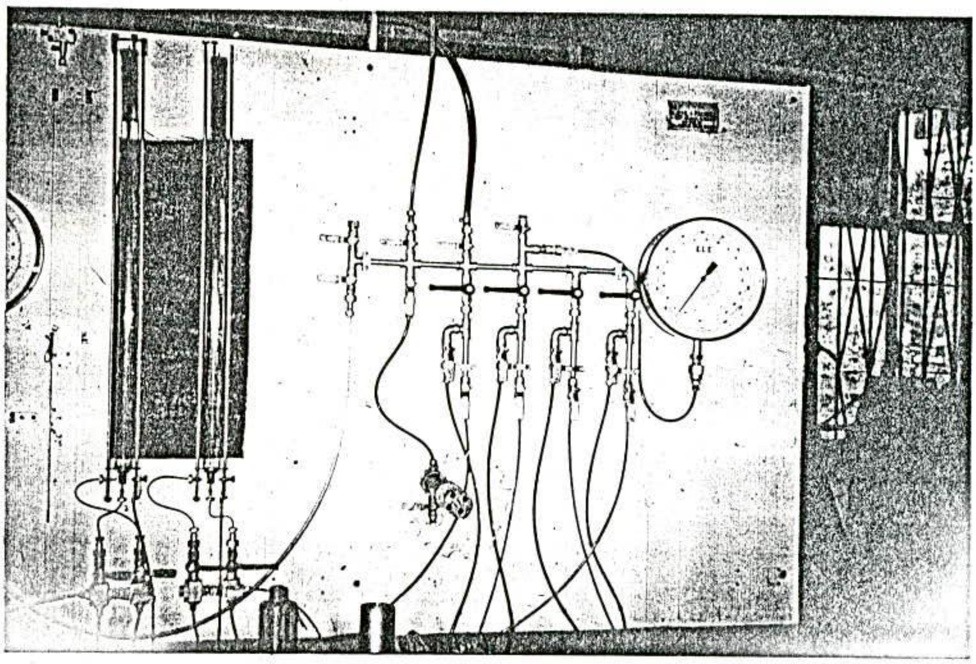
For the present research, a burette system (Bishop and Donald, 1961) has been used for measuring volume change. The burette is of 10 ml volume. It is necessary to measure volume change by the displacement of the surface between two liquids having different densities. Paraffin has been used as the second liquid. Details of the volume change apparatus has been reported by Bishop and Henkel (1962). A red dye is added to the paraffin, and a silicon water repellent is applied to the glass to maintain a meniscus of uniform shape. Volume changes in 10 ml graduated tube can be read to a minimum of 0.02 ml.

3.2.5 MERCURY PORE PRESSURE NULL INDICATOR

The pressure of the water in the pore spaces of the soil sample cannot be measured directly by a pressure gauge or mercury manometer because these devices require the inflow of water to actuate them. Flow of water from the sample would appreciably change the magnitude of the pressure being measured, and would also introduce a time lag in the attainment of a steady reading. These difficulties are overcome by using the 'null method'. A true no-flow condition is ensured by maintaining a water-mercury interface in a capillary tube connected to the base of the sample at a constant level by adjustment of pressure with a manually-operated screw plunger. Null indicator for pore pressure measurement is shown in Fig. 3.5. The development of this principle at Imperial College, London, from 1956 was described by Bishop and Henkel (1962). The modified version



(a)



(b)

Fig. 3.4 Loading system and volume change measurement devices for triaxial machine:

(a) Dash pot and control cylinder, (b) Volume change measurement devi of this device was used for this investigation which is shown in Fig. 3.6. It was made of a single acrylic block and was mounted directly on to the pore pressure outlet from a triaxial cell. A double o-ring seal for rotation eliminating the need for flexible tubing between the mercury thread and the sample.

3.3 TUBE SAMPLERS

3.3.1 FABRICATION OF SAMPLERS

Sample tubes of various dimensions and cutting shoe designs have been previously fabricated from locally available steel tubes. The external diameter and thickness of these tubes were 85 mm and 50 mm respectively.

3.3.2 DIMENSIONS AND DESIGN PARAMETERS OF SAMPLERS

Seven open-drive tube samplers having different cutting shoe designs were fabricated using locally available mild steel pipe. Two categories of samplers were used.

(i) First, samplers with different area ratios, but identical outside cutting edge angle (OCA) were fabricated. The area ratios of these samplers were varied by changing the thickness (t) of the sample tubes while keeping the internal diameter of the samplers constant.

(ii) Second, samplers with varying OCA and identical area ratios were fabricated. The area ratios of all the samplers were the same because the internal diameter (D_i) and external diameter (D_e) of the samplers were the same.

The dimensions and characteristics of the tube samplers are shown in Table 3.1 and the cutting shoe designs of the samplers are shown in Fig. 3.7. Each sampler tube was 127 mm long with no inside clearance (i.e., inside clearance ratio = 0%). . In Table 3.1 and Fig. 3.7, the outside cutting edge angle (OCA) has been defined as the angle between inside face of the cutting shoe and a vertical plane.

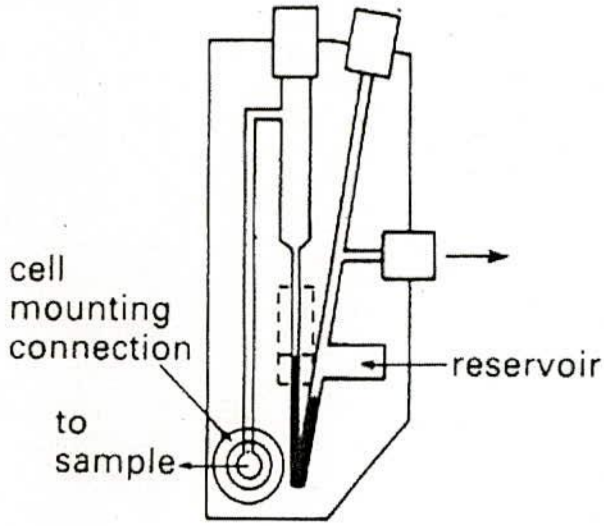


Fig. 3.5 Null indicator for pore pressure measurement

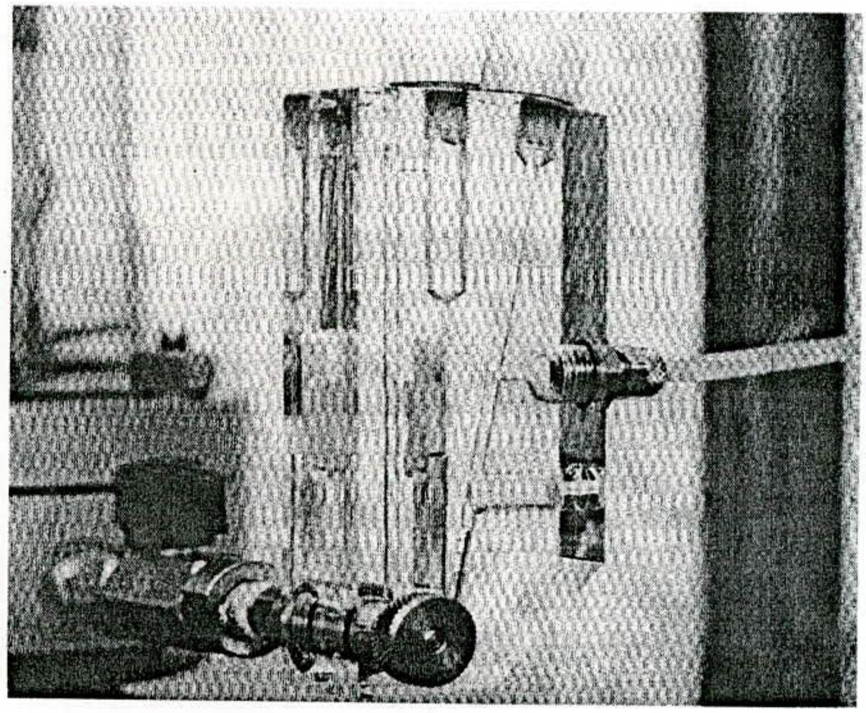


Fig. 3.6 Modified null indicator mounted on pressure outlet from triaxial base pedastal

The area ratio mentioned in Table 3.1 has been defined by the following equation (Hvorslev, 1949):

$$Area\ Ratio = \frac{D_e^2 - D_i^2}{D_i^2} \qquad \ldots(3.1)$$

Table 3.1 Dimensions and Characteristics of the Tube Samplers used.

Sampler (Tube No.)	Thickness, t (mm)	External Diameter, D_e (mm)	Internal Diameter, D_i (mm)	D_e / t Ratio	Area Ratio (%)	OCA (Degree)
T_1	1.5	41	38	27.3	16.4	5
T_2	3.0	44	38	14.7	34.1	5
T_3	4.5	47	38	10.4	53.0	5
T_4	6.0	50	38	8.3	73.1	5
T_5	3.0	44	38	14.7	34.1	10
T_6	3.0	44	38	14.7	34.1	15
T_7	3.0	44	38	14.7	34.1	20

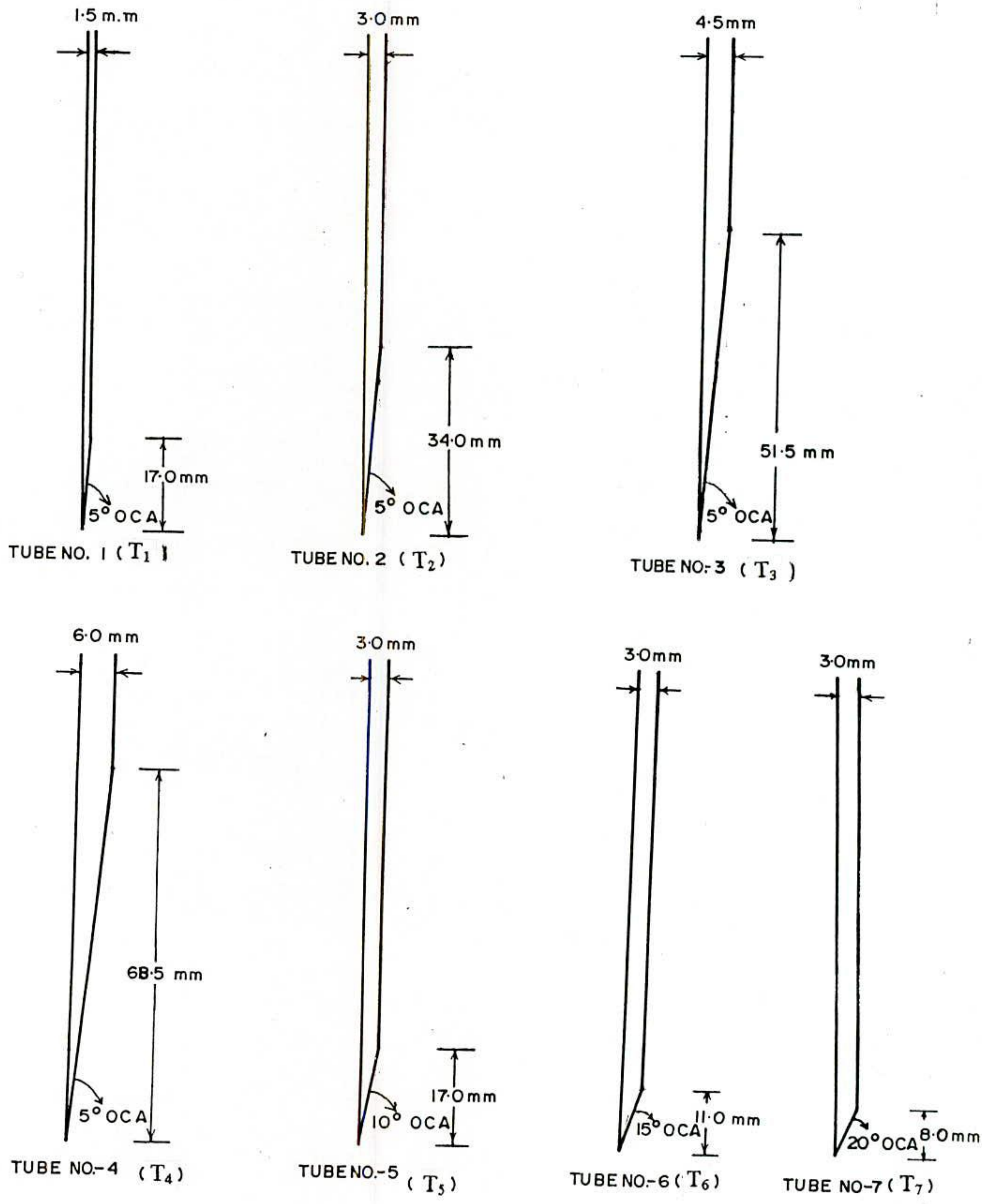


Fig. 3.7 Cutting shoe designs of the tube samplers used

CHAPTER 4

LABORATORY INVESTIGATIONS

4.1 INTRODUCTION

In this chapter, the details of laboratory investigations carried out on Dhaka clay have been described. The different phases of experimental programme are presented in Fig 4.1.

4.2 SAMPLING OF SOIL USED

Red Dhaka clay, collected from Rupnagor Housing Project, Mirpur-11, Dhaka was used in this investigation. Initially, approximately an area of 1 m by 1 m was excavated to a depth of about 1.5 m to 2 m from ground using hand shovels. Proper care was taken to remove any loose material, debris, coarse aggregates and vegetation from the top of the excavated pit. Disturbed samples were collected from the bottom of the borrow pit through excavation by hand shovels. All samples were packed in large polythene bags covered by gunny bags and were eventually transported to the Geotechnical Engineering Laboratory of Bangladesh University of Engineering and Technology (BUET), Dhaka.

4.3 GEOLOGICAL ASPECTS OF DHAKA CLAY

The city of Dhaka situated on the southern part of Modhupurgor which is formed by older Pleistocene Terrace sediments. Dhaka soil belongs mainly to the category of Pleistocene Terraces and some smaller part to Recent Alluvium. Pleistocene and Recent samples do not differ in maximum grain size but an excess of very fine-grained material is found in the Pleistocene samples (Morgan et. al., 1959). Pleistocene sediments are well oxidized and typically are reddish, brown or tan and are mottled. A description of soil profile over Dhaka is provided by Eusufzai (1967) and Ameen (1985).

Mostly of Dhaka soil belongs to Dihing formation of Pleistocene age. This formation having thickness ranging between 8 to 9 meters consists of clay , fine sand and pebbles which are mostly mottled and Red clay. It is also covered by highland and lowland

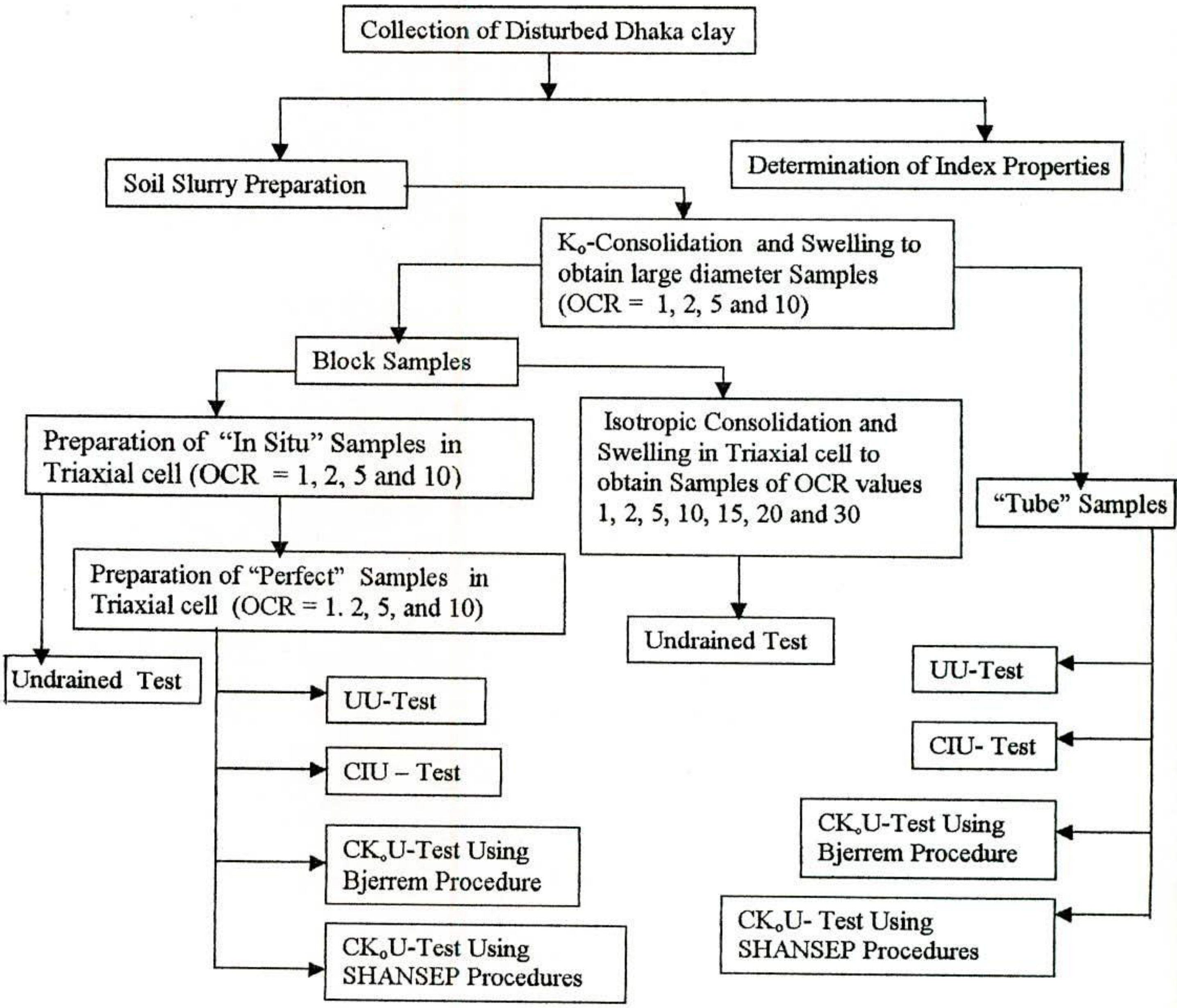


Fig. 4.1 Flow chart for laboratory testing program on reconstituted Dhaka clay

alluvium in some places. Dupi Tila formation underlies the Modhupur clay Residuum which is locally called Dhaka clay. Dupi Tila formation consists of clay, fine sands, medium sands, clayee lenses, sub-ordinate shale and poorly consolidated sand stone, It is massive thick bedded, yellow to yellow brownish in colour.

A portion of east and west side of Dhaka consists of recent alluvium. The alluvium deposit consisting of stream deposits, natural levee and back slope deposits, swamp deposits and inter stream deposits, Though some part of Dhaka is covered by recent alluvium, most of Dhaka soil is of older Pleistocene deposits.

Most of the natural Dhaka soil deposits are at slightly to heavily overconsolidated state. The city of Dhaka is at the elevation of 6 to 8 meters from sea level. The top layer of Dhaka soil generally consists of a mixture of clay and silt. The depth of this top layer varies from 6 meters to 7.5 meters. It is this clay layer that is under research. Layer of coarser materials such as sand and gravel exists at the lower levels and finer particles such as clay and silt dominates at the top surface.

4.4 PHYSICAL AND INDEX PROPERTIES OF THE DHAKA CLAY USED

The samples collected from the field were disturbed samples. These samples were then air-dried and the soil lumps were broken carefully with a wooden hammer so as to avoid breakage of soil particle. The following index properties of the soil were determined:

(i) Specific gravity
(ii) Liquid limit, plastic limit and plasticity Index; and
(iii) Grain size distribution

The specific gravity, liquid limit, plastic limit and plasticity index, and grain size distribution of all the soil sample were determined following the procedures specified in ASTM D854, BS 1377, ASTM D424, ASTM D422 respectively. The clay was also classified according to Unified Soil Classification System (USCS). The index properties and classification of the Dhaka clay are presented in Table 4.1. The grain size distribution curve of the soil is shown in Fig 4.2. On the basis of USCS, the clay is of low to medium plasticity having a group symbol CL.

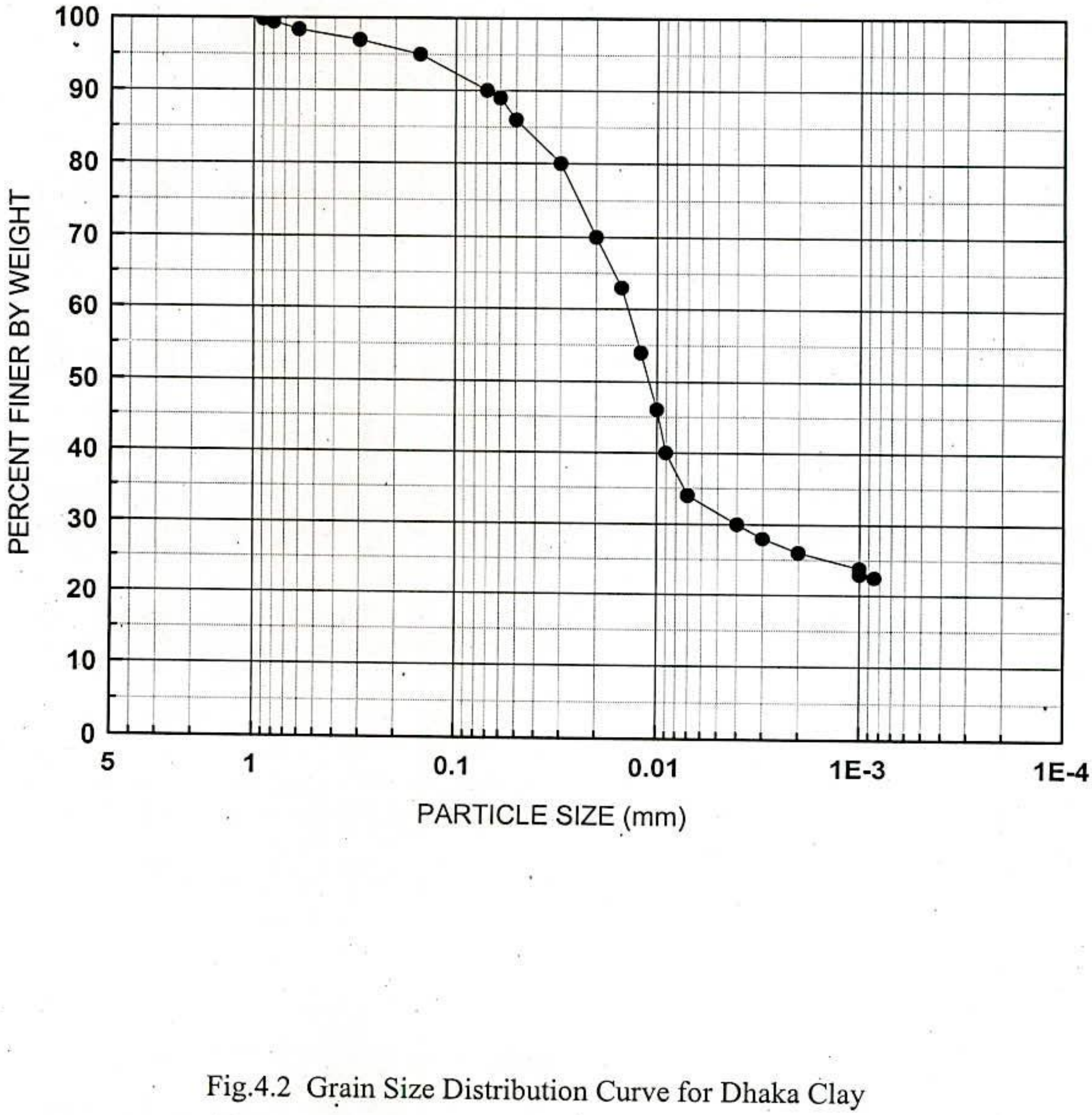


Fig.4.2 Grain Size Distribution Curve for Dhaka Clay

Table 4.1 Index Properties and Classification of Samples of Dhaka Clay Used

Specific Gravity, G_s	Liquid Limit, LL	Plastic Limit, PL	Plasticity Index, PI	Activity, A_c	Grain Size Distribution			USCS Symbol
					Sand (%)	Silt (%)	Clay (%)	
2.69	47	21	26	0.81	11	62	27	CL

4.5 PREPARATION OF RECONSTITUTED SOIL

4.5.1 INTRODUCTION

Reconstituted soils are those which are prepared by breaking down natural soils, mixing them as slurry and reconsolidating them. Reconstituted soils are distinguished from both remoulded soils and from resedimented soils which are mixed as a suspension and allowed to settle from that state. Jardine (1985) discussed the difficulties of implementing detailed investigations of general stress-strain and strength properties using intact samples and it was found that the most comprehensive studies invariably employed reconstituted soil. Reconstituted soil enables a general pattern of behaviour to be established and comparisons with the response of intact samples may be used to identify any special features associated with fabric, stress history or bonding. The major advantages of using data from reconstituted soils are that the ambiguous and substantial effects of sampling of natural soils and inhomogeneity can be eliminated, while the essential history and composition of in-situ soils can be represented. The disadvantages are that the important effect of post-depositional process, such as ageing, leaching, etc. and variations of composition and fabric are not included. So the pattern of behaviour for reconstituted soils discussed in the following chapters will be taken to represent that of young or unaged soils where no post-depositional processes have operated.

4.5.2 PREPARATION OF SOIL SLURRY

Clay slurry with an initial water content well beyond the liquid limit had been commonly used as an initial state for samples preparation (Siddique, 1990; Hopper, 1992; Sarker, 1994, Farooq, 1995). Higher initial water contents provide higher degrees of saturation and higher freedom of particle orientation but require larger initial volumes and longer consolidation periods. Since, large volume of clay was required for preparing enough samples and also in order to reduce the consolidation time, it was essential to use an initial water content sufficient to yield a uniform and homogeneous slurry. The samples were first air dried and powdered with the help of a motorised grinding machine. The powdered samples were then sieved through No. 40 sieve and the sieved samples were mixed with water at 1.0 times to 1.5 times the liquid limit to form soil slurry. The soil and water were thoroughly mixed by hand kneading to form slurry to ensure full saturation. The soil-water mix was then further mixed uniformly by using rotary laboratory mixer for about 30 minutes.

4.5.3 CONSOLIDATION OF SLURRY

For K_0-consolidation of slurry to form a uniform soil cake, a cylindrical consolidation cell of 260 mm diameter and 305 mm in height was used. A wire net and a 6 mm thick perforated steel disc were placed at the bottom of the mould of the cell. The wall of the cell was coated with a thin layer of silicon grease to minimise side friction and two filter papers were placed over the disc at the bottom of the cell. The slurry was then poured into the K_0-consolidation cell and stirred with steel rod to remove the entrapped air from the slurry. After removing air bubble, the top surface of the soil samples was levelled properly. At the top of the slurry, two filter papers followed by two perforated discs were placed to permit drainage. A wire net was used between the two discs for easy flow of water in the horizontal direction. A clearance of a few millimetres in between the perforated discs and inside edge of the cell was provided to eliminate side friction. Arrangements for preparation of reconsolidated sample in K_0-consolidation cell is shown in Fig. 4.3.

An axial load of 150 kN/m^2 was gradually applied to the sample using a loading frame with proving ring. At first, the sample was subjected to consolidate by the self weight of the sample and the weight of the porous discs for about 24 hours. Then a pressure of 15 kN/m^2 was applied to the sample for the next 24 hours. Similarly, pressure was increased gradually

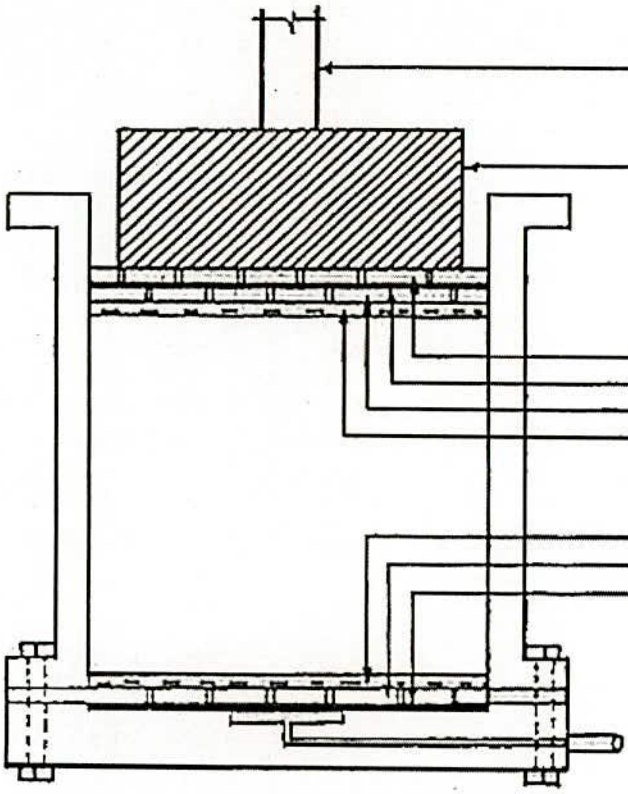


Fig. 4.3 Arrangements for Preparation of Reconstituted sample in K_0-Consolidation Cell

to the required value of 150 kN/m^2. This pressure (150 kN/m^2) was maintained until the end of primary consolidation, which was indicated by the constant reading of compression dial gauge. It took about nine to ten days for the completion of primary consolidation. Rate of compression had been very fast at initial stage of consolidation and then it gradually decreased with time. A plotting of volume change versus logarithm of time is shown in Fig 4.4. Large block samples of reconstituted normally loaded consolidated (OCR =1) soil were prepared from slurry by consolidation in a big steel cylindrical mould by applying a maximum vertical effective stress of 150 kN/m^2. In order to prepare overconsolidated samples of OCR values of 2, 5 and 10, the vertical maximum vertical effective stress of 150 kN/m^2 was reduced to 75 kN/m^2, 30 kN/m^2 and 15 kN/m^2, respectively and maintained up to three days for swelling. After the completion of consolidation and swelling (for overconsolidated samples), the top and bottom part of the cell were separated and the soil cake was extruded by using a mechanical extruder. A soil cake of about 125 mm to 150 mm (5 to 6 inch) thickness was obtained by the above procedure. The uniformity in density and moisture content of the prepared soil cake was checked from moisture content and density of at least five specimens. Water contents of the reconstituted overconsolidated soil samples for OCR values of 1, 2, 5 , and 10, were 28 ± 0.5%, 28.5 ± 0.5%, 29 ± 0.5% and 30 ± 0.5%, respectively. The bulk density of the reconstituted overconsolidated soil samples for OCR values of 1, 2, 5 and 10 were 19.5 ± 0.2 kN/m^3, 19 ± 0.2 kN/m^3 , 18.5 ± 0.3 kN/m^3 and 18.2 ± 0.3 kN/m^3, respectively.

4.6 K_0 OF SOIL SAMPLES

The value of K_0 of Dhaka clay sample was determined from a series of anisotropic continuous loading consolidation tests with different stress ratios (σ_r'/σ_a'). The stress ratio for which the axial strain (ε_a) during consolidation is approximately equal to volumetric strain (ε_v) has been taken to be the value of K_0.The approximate value of K_0 of the normally consolidated Dhaka clay used has been found to be 0.50 .

4.7 TYPES OF TEST SAMPLES

4.7.1 "IN SITU" SAMPLE

The soil cake prepared by K_0-consolidation will be extruded from the consolidation cell. The cake were sliced by the wire knife into small blocks and samples of nominal

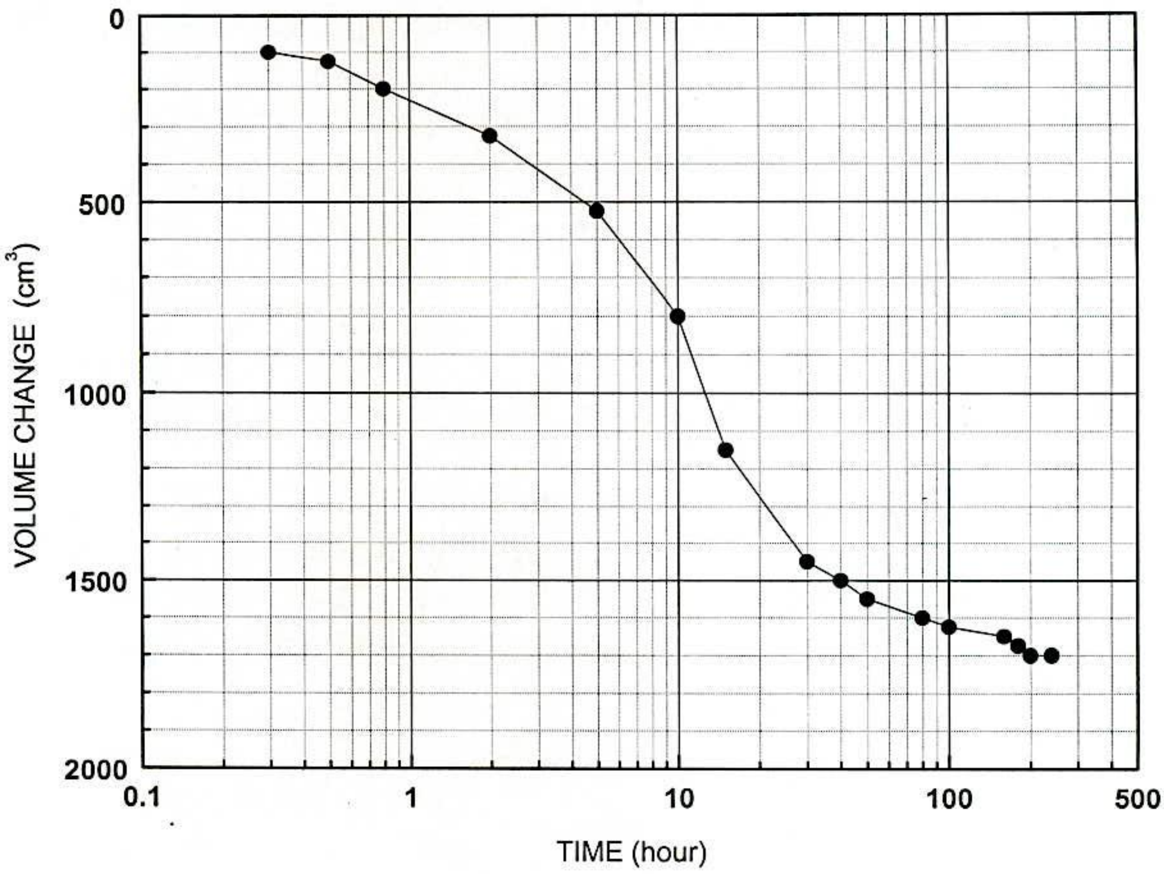


Fig. 4.4 Volume Change Versus Logarithm of Time Curve for the Consolidation of Slurry of Dhaka Clay.

dimensions of 38 mm diameter by 76 mm high samples were prepared by trimming these blocks using piano wire, a soil lathe and a split mould. These samples were first consolidated under K_0-condition in the triaxial cell to its "in situ" vertical effective stress, σ'_{vc}, i.e., 150 kN/m^2 to prepare normally consolidated sample (i.e., OCR = 1). The maximum vertical effective stress of 150 kN/m^2 was reduced to 75 kN/m^2, 30 kN/m^2 and 15 kN/m^2 to prepare samples of OCR values of 2, 5 and 10, respectively. A back pressure of 270 kN/m^2 was used during K_0-consolidation and swelling of the samples. These samples have been termed as "in situ" samples.

4.7.2 "PERFECT" SAMPLE

"Perfect" samples were prepared from the respective "in situ" samples in the triaxial cell. Deviator stress of the "in situ" sample was first released and then the cell pressure was reduced to zero. At this stage, the sample was subjected to zero total stress. These samples have been termed as "Perfect".

4.7.3 "TUBE" SAMPLE

Tube samplers of different area ratio, D_e / t ratio and outside cutting edge angle (OCA), as mentioned in Table 3.1, were steadily pushed into the soil cake of different OCR-values. The samples were then extruded mechanically from the tubes. The extruded samples were trimmed to nominal dimensions of 38 mm diameter by 76 mm high. These samples have been termed as "tube" samples. The sample designations of the different types of samples have been presented in Table 4.2.

4.8 TESTING PROGRAMME

The whole laboratory test programme consisted of carrying out the following five types of tests:

(1) The first type of test carried out was undrained triaxial compression test on four "in situ" samples of OCR values of 1, 2, 5 and 10 in order to determine the reference undisutrbed behaviour of the soils. In this test, after the completion of K_0-consolidation (for sample of OCR = 1) and K_0-consolidation and swelling (for samples of OCR = 2, 5 and 10), the sample was sheared in undrained triaxial compression at a deformation

Table 4.2 Designations of "In Situ", "Perfect" and "Tube" Samples of Dhaka clay.

Sample Type	Sampler for Sampling	Sample Designation			
		OCR = 1	OCR = 2	OCR = 5	OCR = 10
"In Situ"	-	OCR_1-I	OCR_2-I	OCR_5-I	OCR_{10}-I
"Perfect"	-	OCR_1-P	OCR_2-P	OCR_5-P	OCR_{10}-P
"Tube"	T_1	OCR_1-T_1	OCR_2-T_1	OCR_5-T_1	OCR_{10}-T_1
"Tube"	T_2	OCR_1-T_2	OCR_2-T_2	OCR_5-T_2	OCR_{10}-T_2
"Tube"	T_3	OCR_1-T_3	OCR_2-T_3	OCR_5-T_3	OCR_{10}-T_3
"Tube"	T_4	OCR_1-T_4	OCR_2-T_4	OCR_5-T_4	OCR_{10}-T_4
"Tube"	T_5	OCR_1-T_5	OCR_2-T_5	OCR_5-T_5	OCR_{10}-T_5
"Tube"	T_6	OCR_1-T_6	OCR_2-T_6	OCR_5-T_6	OCR_{10}-T_6
"Tube"	T_7	OCR_1-T_7	OCR_2-T_7	OCR_5-T_7	OCR_{10}-T_7

rate of 0.02 mm/min. A back pressure of 270 kN/m^2 had been used during K_0-consolidation and swelling of the samples

(2) The second type of test was unconsolidated undrained (UU) triaxial compression tests on twenty eight "tube" samples. In these tests, soon after the completion of saturation, the samples were sheared at a deformation rate of 0.020 mm/minute in compression under undrained condition.

(3) The third type of test was by unconsolidated undrained (UU) triaxial compression test on four "perfect" samples of OCR values of 1, 2, 5 and 10. In these tests, after the simulation of "perfect" sampling in the triaxial cell, each sample was subjected to a cell pressure equal to the respective effective vertical stress of the 'in situ" sample. After the equalisation of pore pressure, the sample was sheared at a deformation rate of 0.020 mm/minute in compression under undrained condition.

(4) The fourth type of test was undrained triaxial compression tests on seven isotropically consolidated (OCR = 1) and isotropically consolidated and swelled (OCR values of 2,

5, 10, 15, 20 and 30) samples of reconstituted Dhaka clay. The normally consolidated sample was consolidated using a cell pressure of 150 kN/m^2. Each overconsolidated sample was initially consolidated using a cell pressure of 150 kN/m^2 and then the samples were allowed to swell by reducing the cell pressures to 75 kN/m^2, 30 kN/m^2, 15 kN/m^2, 10 kN/m^2, 7.5 kN/m^2, and 5 kN/m^2 for the samples of OCR values of 2, 5, 10, 15, 20 and 30, respectively. The normally consolidated and overconsolidated samples were then sheared to failure in undrained triaxial compression at a deformation rate of 0.02 mm/min.

(5) The fifth type of test was undrained triaxial compression tests on reconsolidated "tube" samples obtained with sampler tube T2 (Area ratio = 34.1 %, t = 3.0 mm, D_e/t ratio = 14.7 and OCA = 5°) and reconsolidated "perfect" samples of OCR values of 2 and 10. In these tests, after the completion of reconsolidation, the samples were sheared at a deformation rate of 0.02 mm/minute in compression under undrained condition.

The following three reconsolidation procedures were adopted to assess the effect of reconsolidation of "tube" and "perfect" samples:

(i) Isotropic Reconsolidation : In this reconsolidation procedure, a hydrostatic consolidation stress equal to the in situ effective vertical stress was used (i.e., 75 kN/m^2 and 15 kN/m^2 for the samples of OCR values of 2 and 10, respectively).

(ii) Anisotropic reconsolidation using Bjerrum (1973) procedure : In this reconsolidation procedure samples were reconsolidated under K_0-condition up to vertical effective stress of the "in situ" sample.

(iii) Anisotropic reconsolidation using SHANSEP (Ladd and Foott, 1974) procedures: In these reconsolidation procedures, samples were reconsolidated under K_0-condition using vertical effective stresses equal to 1.5 and 2.5 times the effective vertical stress (σ'_{vc}) of the "in situ" sample

4.9 TEST PROCEDURES

4.9.1 UNDRAINED TRIAXIAL COMPRESSION TEST ON "IN SITU" SAMPLES

Conventional monotonic undrained triaxial compression tests were performed on four "in situ" samples of OCR values of 1, 2, 5 and 10.

Preparation of "In Situ" Sample

The porous discs and filter paper were removed from the top of the consolidated soil cake. The cake was then sliced by the wire knife into small blocks and samples for specimen of nominal dimensions of 38 mm diameter by 76 mm high were prepared by trimming these blocks using piano wire, a soil lathe and a split mould. The weight of the specimen was taken and its water content was determined. After that, the following procedures have been adopted for preparing "in situ" sample:

(1) Prior to placing the trimmed sample and cylindrical cell cap, the top and bottom drainage lines along with volume change indicator were flushed separately with deaired water.

(2) To avoid entrapped air in the line, water was allowed to run slowly. After flushing, the drainage control valves were closed.

(3) One filter paper followed by one porous stone was placed at each end of the soil sample and vertical strip of filter paper were used along the periphery of the sample to permit double drainage and drainage from radial boundary respectively during consolidation. Each sample of known weight was enclosed in a rubber membrane with the help of membrane stretcher and was placed in the cell. The top cap was placed properly and the top and bottom rubber "O" rings were placed over the rubber membrane.

(4) By raising the top nut and upper assembly, the cell cap was placed and three clamps were fixed properly so that the apex of the loading ram was just in contact with the centrally placed ball of the top cap.

(5) The cell was filled with water by opening the bleed valve which was at the top of upper assembly. After filling the cell chamber, the bleed valve was closed.

(6) At this stage, the sample was kept under a cell pressure of 34.5 kN/m^2 (5 psi) using a dash pot and control cylinder system and back pressure of 24.1 kN/m^2 (3.5 psi) using an overhead water bottle for overnight saturation to remove the entrapped air bubbles within the sample. Both bottom and top drainage lines were kept open. The bottom drainage line was connected to the back pressure system and the top drainage line was subjected to atmospheric pressure.

(7) The proving ring and strain gauge were placed. The base of the cell was raised slowly by operating the wheel handle manually until the proving ring was just in contact with

the top of the loading ram. This was showed by the movement of the proving ring dial gauge indicator.

(8) At this stage, the sample was saturated by gradually increasing the cell pressure and back pressure using the dash pot and control cylinder system until the B-value of the sample reached 0.90 or above. The volume change of the sample and the corresponding axial strain were also measured. Immediately after saturation, effective cell pressure applied to the sample was 6.89 kN/m^2 (1 psi).

(9) At this stage, the required effective radial stress required for K_0-consolidation was generated by using the dash pot and control cylinder system. The drainage valves were opened and total deviator load was applied in small increments to attain K_0-condition. During this operation excess pore water pressure was generated within the sample. The sample was then allowed to consolidate until the excess pore water pressure completely dissipated. During K_0-consolidation the volume change and the compression of the sample were measured. After completion of consolidation, the sample thus obtained in the triaxial cell has been termed as normally consolidated "in situ" sample (i.e., OCR = 1).

(10) To prepare "in situ" samples of OCR values of 2, 5, and 10, the maximum "in situ" vertical effective stress (σ'_{vc}), i.e., 150 kN/m^2 was reduced to 75 kN/m^2, 30 kN/m^2, and 15 kN/m^2, respectively, and the samples were allowed to swell.

Shearing of "In Situ" Sample

The shearing of "in situ" samples were carried out in the triaxial cell in accordance with the following procedure:

(1) The drainage valves were closed and the strain gauge was set at zero position. The proving ring dial gauge reading and the corresponding Mercury pore pressure null indicator or pore pressure transducer reading were recorded.

(2) The sample was then sheared and the proving dial gauge readings and the corresponding Mercury pore pressure null indicator readings were recorded at specified deformation of the sample. A deformation rate of 0.02 mm/minute was used. Shearing was continued until the proving ring dial reading remained constant or decreased for a few readings of strain dial gauge.

(3) At the end of the test, cell base was lowered and cell pressure was released. The cell was disassembled and sample was carefully removed from the cell. The weight of the sample was taken and its water content was determined.

4.9.2 UNCONSOLIDATED UNDRAINED (UU) TRIAXIAL COMPRESSION TEST ON "TUBE" SAMPLES

A total of 28 UU triaxial compression tests were carried out on "tube" samples having OCR values of 1, 2, 5 and 10. These tests were performed in two stages. Firstly, the steps (1) to (8) as mentioned in Article 4.9.1 was carried out. A cell pressure equal to the effective overburden pressure of the respective "in situ" sample was applied (i.e., 150 kN/m^2, 75 kN/m^2, 30 kN/m^2, and 15 kN/m^2 for samples of OCR values of 1, 2, 5 and 10, respectively). Finally, each sample was sheared in compression under undrained condition at a constant deformation rate of 0.02 mm/min.

4.9.3 UNDRAINED TRIAXIAL COMPRESSION TEST ON "PERFECT" SAMPLE

The undrained triaxial compression tests were carried out on "perfect" samples of OCR values of 1, 2, 5, and 10. At first K_0-consolidation performed on each sample under in situ stress. K_0-consolidation was carried out following the steps (1) to (9) mentioned in Article 4.9.1. After completion of K_0-consolidation the following procedure was adopted:

(1) Top and bottom drainage valves were closed.

(2) Deviator stress, i.e., in situ shear stress was unloaded and the pore pressure reading was recorded. At this stage the sample was subjected to only an isotropic effective stress.

(3) The sample was then subjected to zero total stress by reducing the cell pressure to zero. This was done by reducing the cell pressure to zero.

Following the above procedure "perfect" sampling was simulated in the triaxial cell. At this stage, a cell pressure equal to that required for isotropic consolidation was applied to the sample. The Mercury pore pressure null indicator reading was recorded at the steady state. At the same time, the proving ring dial gauge reading was recorded and strain dial gauge was set at zero position. Then the sample was sheared in compression under undrained condition at a constant deformation rate of 0.02 mm/min.

4.9.4 ISOTROPICALLY CONSOLIDATED UNDRAINED (CIU) TRIAXIAL COMPRESSION TEST ON NORMALLY CONSOLIDATED AND OVERCONSOLIDATED SAMPLES

Seven undrained triaxial compression tests were carried out on undisturbed block samples having OCR values of 1, 2, 5, 10, 15, 20 and 30. In these tests, for each sample initially the procedures mentioned in steps (1) to (8) in Article 4.9.1 were followed for undisturbed normally consolidated block samples having nominal dimensions of 38 mm diameter by 76 mm high. The sample of OCR value of 1 was consolidated isotropically using an effective consolidation pressure of 150 kN/m^2. In order to prepare samples of OCR values of 2, 5, 10, 15, 20 and 30, each sample was initially consolidated using a maximum effective consolidation pressure of 150 kN/m^2 which was then reduced to 75 KN/m^2, 30 KN/m^2, 15 KN/m^2, 10 KN/m^2, 7.5 KN/m^2 and 5 KN/m^2, respectively. A back pressure of 270 kN/m^2 was maintained during consolidation and swelling. Finally, each sample was sheared in compression under undrained condition at a constant deformation rate of 0.02 mm/min.

4.9.5 ISOTROPICALLY CONSOLIDATED UNDRAINED (CIU) TRIAXIAL COMPRESSION TEST ON OVERCONSOLIDATED"TUBE" AND "PERFECT" SAMPLES

In this test, initially the procedures mentioned in steps (1) to (8) in Article 4.9.1 were followed for "tube" samples having OCR values of 2 and 10, and the procedures mentioned in Article 4.9.3 to simulate "perfect" sampling in the triaxial cell were followed for "perfect" samples of OCR 2 and 10. The samples were then allowed to consolidate isotropically using the respective vertical effective stress (σ'_{vc}) of the "in situ" sample (i.e., 75 kN/m^2 and 15 kN/m^2 for the samples of OCR values of 2 and 10, respectively). A back pressure of 270 kN/m^2 was maintained during consolidation. The volume change and consolidation of the sample were monitored. Consolidation was continued until the volume change indicator showed constant reading. After completion of consolidation, the samples were sheared in compression under undrained condition at a constant deformation rate of 0.02 mm/min.

4.9.6 K_0-CONSOLIDATED UNDRAINED (CK_0U) TRIAXIAL TEST ON OVERCONSOLIDATED "TUBE" AND "PERFECT" SAMPLES USING BJERRUM PROCEDURE

In CK_0U triaxial compression tests using Bjerrum (1973) procedure, firstly the procedure mentioned at steps (1) to (8) in Article 4.9.1 were followed for "tube" samples having OCR values of 2 and 10, and the procedures mentioned in Article 4.9.3 to simulate "perfect" sampling in the triaxial cell were followed for "perfect" samples of OCR 2 and 10. At this stage, the required effective radial stress required for K_0-consolidation was generated by using the dashpot and control cylinder system. The drainage valves were opened and total deviator load was applied in small increments to attain K_0-condition. The samples were consolidated under K_0-condition up to vertical effective stress of the respective "in situ" sample (i.e., 75 kN/m^2 and 15 kN/m^2 for the samples of OCR values of 2 and 10, respectively). During this operation excess pore water pressure was generated within the sample. The sample was then allowed to consolidate until the excess pore water pressure completely dissipated. During K_0-consolidation the volume change and compression of the sample were measured. After completion of consolidation, the samples were sheared in compression under undrained condition at a constant deformation rate of 0.02 mm/min.

4.9.7 K_0-CONSOLIDATED UNDRAINED (CK_0U) TRIAXIAL TEST ON OVERCONSOLIDATED "TUBE" AND "PERFECT" SAMPLES USING SHANSEP PROCEDURES

These tests on four "tube" and four "perfect" samples of OCR values of 2 and 10. The sample tube of area ratio = 34.1% (t = 3.0 mm) and outside cutting edge angle of 5° was used to collect "tube" samples. Firstly the procedure mentioned at steps (1) to (8) in Article 4.9.1 were followed for "tube" samples having OCR values of 2 and 10, and the procedures mentioned in Article 4.9.3 to simulate "perfect" sampling in the triaxial cell were followed for "perfect" samples of OCR 2 and 10. At this stage, the required effective radial stress for K_0-consolidation was generated by using the dashpot and control cylinder system. The drainage valves were opened and total deviator load was applied in small increments to attain K_0-condition. The overconsolidated "tube" and "perfect" samples were consolidated under K_0-condition up to 1.5 and 2.5 times the vertical effective stress of the respective "in situ" sample (i.e., 112.5 kN/m^2 and 187.5 kN/m^2 for the samples of OCR 2 and 22.5 kN/m^2 and 37.5 kN/m^2 for the samples of OCR 10). During this operation excess pore water pressure was generated within the sample. The sample was then allowed to consolidate until the excess pore water pressure completely dissipated. During K_0-consolidation the volume change and compression of the sample were measured. After completion of consolidation, the samples were sheared in compression under undrained condition at a constant deformation rate of 0.02 mm/min.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 INTRODUCTION

The findings of the laboratory investigations on "in situ", "tube" and "perfect" samples of normally consolidated and overconsolidated (OCR = 2, 5 and 10) Dhaka clay are presented in this chapter. The stress-strain-strength, stiffness and pore pressure characteristics of soil samples are discussed to examine the influence of tube and perfect sampling on the behaviour of normally consolidated and overconsolidated Dhaka clay. Attempt has been made to assess the influence of cutting shoe geometry of tube sampler on the measured undrained soil parameters of Dhaka clay. The suitability of various reconsolidation procedures to minimize tube and perfect sampling disturbance effects has also been examined.

5.2 BEHAVIOUR OF "IN SITU" SAMPLES

Untrained triaxial compression tests on "in situ" samples were performed to determine the reference undisturbed behaviour of the normally consolidated and overconsolidated Dhaka clay.

5.2.1 STRESS PATHS

Effective stress paths in s′-t′ [$s' = (\sigma_a' + \sigma_r')/2$, $t' = (\sigma_a' - \sigma_r')/2$] space for undrained test on "in situ" of the normally consolidated and overconsolidated samples of Dhaka clay are shown in Fig. 5.1. It can be seen from Fig. 5.1 that the effective stress paths are typically identical to that of reconstituted normally consolidated and overconsolidated clays. It can also be seen from Fig. 5.1 that the nature of effective paths of overconsolidated samples, are similar, while that for the normally consolidated sample is markedly different.

5.2.2 STRESS-STRAIN-STRENGTH, STIFFNESS AND PORE PRESSURE CHARACTERISTICS

Fig. 5.2 shows plots of deviator stress versus axial strain for normally consolidated and overconsolidated "in situ" samples of Dhaka clay. The stress-strain curves of the "in situ" samples show following features:

(1) The peak undrained strength is mobilized at relatively large axial strain.

(2) The strength mobilized at ultimate strain is slightly lower than that mobilized at peak. The clay, therefore, does not show any undrained brittleness or strain hardening behaviour when sheared in compression.

(3) The stress-strain relationships are nonlinear.

The undrained shear strength (s_u), axial strain at peak deviator stress (ε_p), initial tangent modulus, (E_i) and secant stiffness at half of the peak deviator stress (E_{50}) of the four "in situ" samples were determined from the stress-strain data and the undrained shear parameters are presented in Table 5.1. The test results are not corrected with respect to water content. It can be seen from Table 5.1 that undrained shear strength for the soils of Dhaka clay for OCR values of 1, 2, 5, and 10, varied between 56.6 kN/m^2 and 46.6 kN/m^2. The variation of strength ratio with overconsolidation ratio (OCR) for "in situ" samples of Dhaka clay is shown in Fig. 5.3. It can be seen from Fig. 5.3 that strength ratio increases with increasing OCR for "in situ" samples of Dhaka clay. Similar behavior has also been reported for the reconstituted Dhaka clay (Ameen, 1985; Kamaluddin, 1990). It can be seen from Table 5.1 that ε_p reduces with increasing OCR values. In Fig. 5.4, secant stiffness up to 1% axial strain have been plotted for the normally consolidated and overconsolidated "in situ" samples of Dhaka clay. It can be seen from Fig. 5.4 that stiffness decreases sharply with increasing levels of strains. Similar trend has also been reported for the "in situ" normally consolidated reconstituted clays (Farooq, 1995; Hajj, 1990; Hopper, 1992, Siddique et al., 1999).

The variation of normalized stiffness ratios, E_i/σ_{vc}' and E_{50}/σ_{vc}' with OCR for "in situ" samples of Dhaka clay is shown in Fig. 5.5. The both stiffness ratios, E_i/σ_{vc}' and E_{50}/σ_{vc}' increase with increasing OCR for "in situ" samples of Dhaka clay.

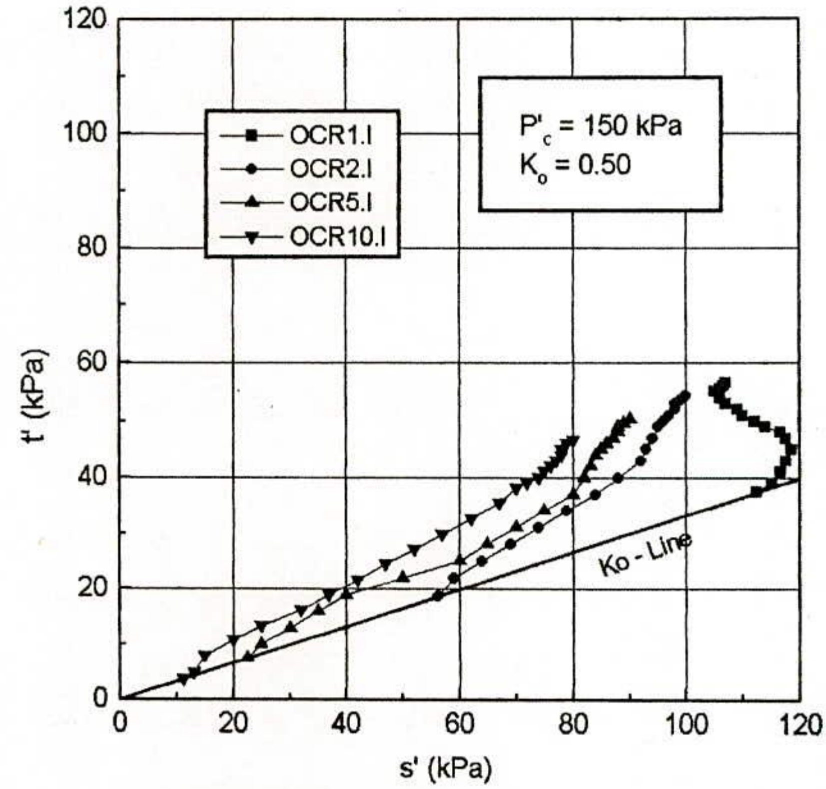


Fig.5.1 Effective stress paths of Normally consolidated and Overconsolidated "in situ" samples of Dhaka Clay.

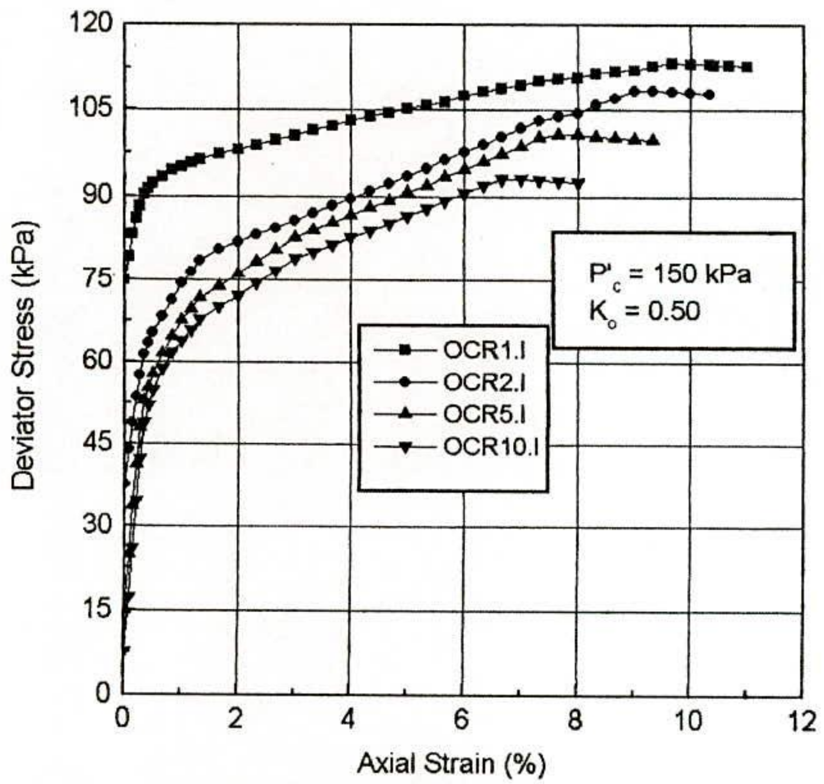


Fig. 5.2. Deviator Stress Vs. Axial Strain (%) Plots of Normally consolidated and Overconsolidated "in situ" samples of Dhaka Clay.

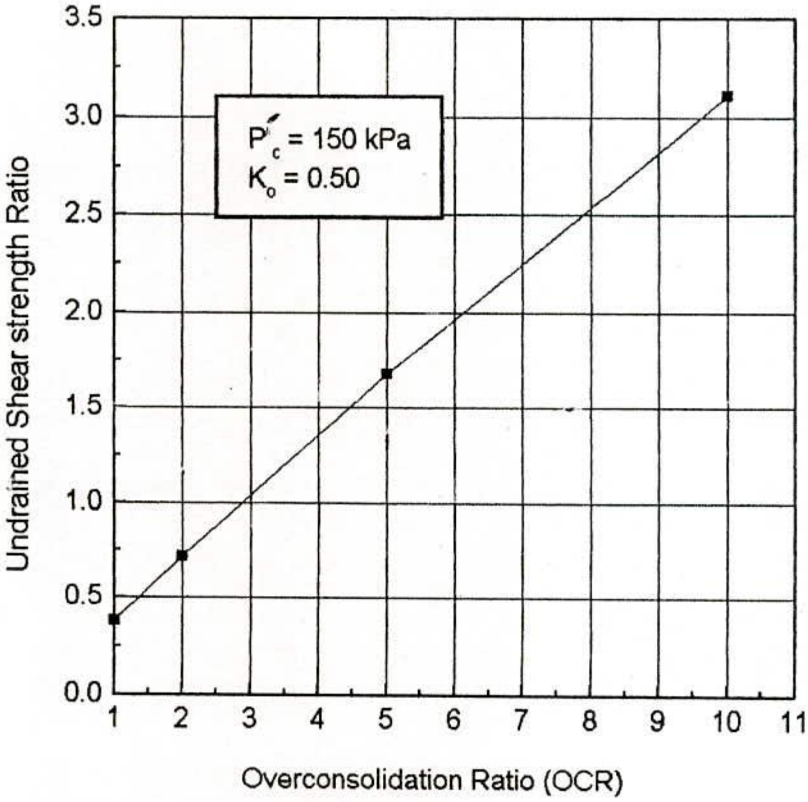


Fig.5.3 Variation of Undrained Shear strength Ratio (s_u / σ'_{vc}) with Overconsolidation Ratio (OCR) for "in situ" samples of Dhaka clay.

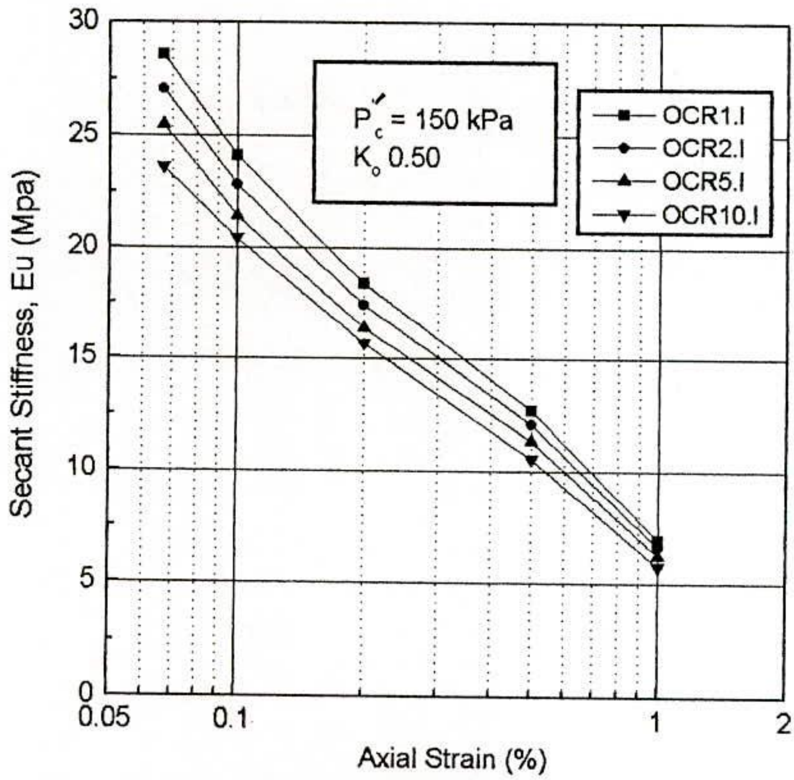


Fig.5.4 Secant stiffness vs. Axial strain plots of Normally consolidated and Overconsolidated "in situ" samples of Dhaka Clay.

The response of pore pressure was observed throughout the whole shearing stage for each "in situ" sample. The change in pore pressure versus axial strain plots for the normally consolidated and overconsolidated samples of Dhaka clay are shown in Fig. 5.6. It can be seen from Fig. 5.6 that during undrained shearing the pore pressure increases rapidly with the increase in deviator stress for strain levels of about 3.0% to 4.0%. After reaching the peak value (at 4.5% to 6.5% strain levels), change in pore pressure reduces with increase in axial strain. It can be seen from Fig. 5.6 that pore pressure change for normally consolidated sample due to increase in deviator stress is higher than that of the overconsolidated samples. It is also evident that change in pore pressure decreases with increase in overconsolidation ratio of samples. Skempton's pore pressure parameter A at peak deviator stress (A_p) of the "in situ" samples of Dhaka clay are also shown in Table 5.1. It can be seen from Table 5.1 that the values of A_p varied from 0.42 to 0.13. The variation of A_p with OCR for "in situ" samples of Dhaka clay is shown in Fig. 5.7. It is observed from Fig. 5.7 that Skempton's pore pressure parameter A at peak deviator stress (A_p) of Dhaka clay decreases with the increase in OCR.

Table 5.1 Undrained Shear Properties of "In Situ" Samples of Normally Consolidated and Overconsolidated Dhaka Clay.

Sample Designation	s_u (kN/m^2)	ε_p (%)	E_i (kN/m^2)	E_{50} (kN/m^2)	A_p	s_u / σ'_{vc}
OCR_1-I	56.6	9.7	28500	22950	0.42	0.38
OCR_2-I	54.2	9.0	26530	21750	0.19	0.72
OCR_5-I	50.4	7.6	24380	20450	0.14	1.68
OCR_{10}-I	46.6	6.7	22230	18950	0.13	3.11

5.3 INFLUENCE OF TUBE SAMPLING DISTURBANCE IN NORMALLY CONSOLIDATED AND OVERCONSOLIDATED DHAKA CLAY

In order to investigate the effect of tube sampling on undrained shear behaviour, triaxial compression tests were carried out on samples collected with samplers of varying area ratio (and

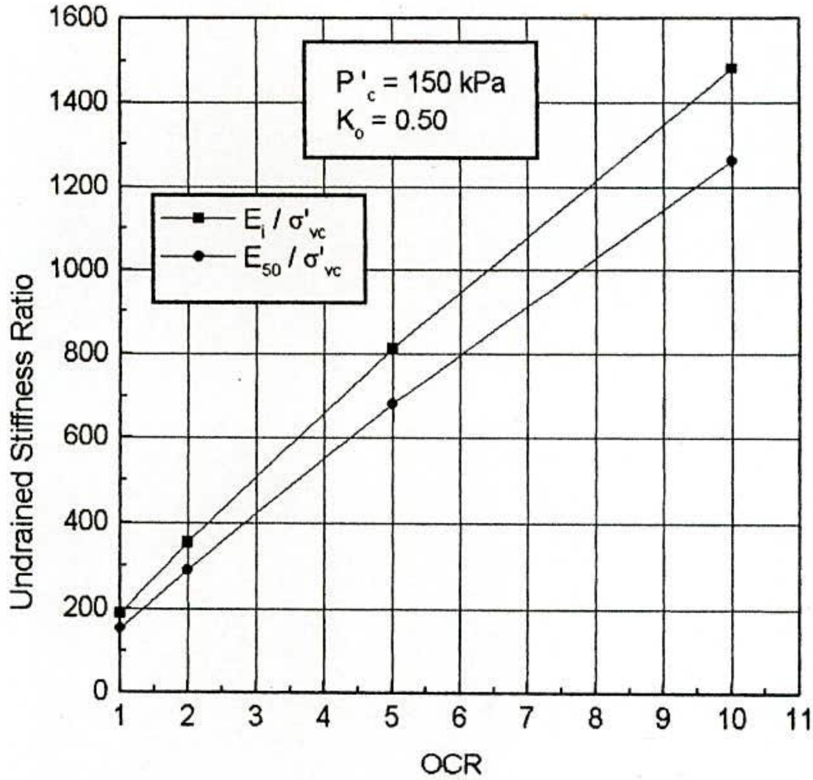


Fig.5.5 Variation of Undrained Stiffness Ratio with Overconsolidation Ratio (OCR) for "in situ" samples of Dhaka clay.

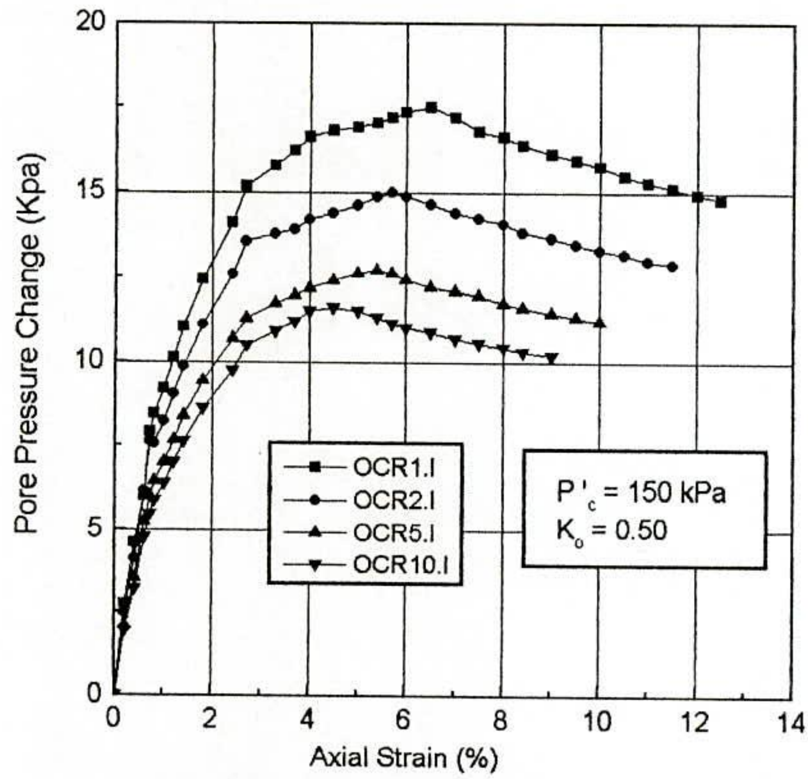


Fig.5.6 Pore pressure response for Normally consolidated and Overconsolidated "in situ" samples of Dhaka Clay.

as such of different D_e/t ratio) and of varying outside cutting edge taper angle (OCA). The design parameters of these samplers and designations of samples retrieved with these samplers have previously been presented in Table 3.1 and Table 4.2 respectively. Initial effective stress, undrained stress-strain-strength, stiffness and pore pressure characteristics of normally consolidated and overconsolidated "tube" samples of Dhaka clay, were determined from unconsolidated undrained (UU) triaxial compression tests. The test results are presented and discussed in the following sections.

5.3.1 INITIAL EFFECTIVE STRESS

In order to determine initial effective stress, relatively high cell pressure was applied on sample under undrained condition and a steady pore pressure generated within the sample was recorded. Initial effective stress have been calculated by subtracting pore water pressure from all-round cell pressure (Skempton, 1961). The isotropic effective stress, σ_{ps}' of "perfect" samples of normally consolidated and overconsolidated has been determined using Equation 2.5. The values of σ_{ps}' of Dhaka clay for OCR values of 1, 2, 5, and 10 have been found to be 88.7 kN/m^2, 40.4 kN/m^2, 15.1 kN/m^2 and 7.2 kN/m^2 respectively. Tables 5.2 shows the comparison of initial effective stress of "tube" samples collected by tubes of different sampler geometry with isotropic effective stress of respective "perfect" samples of Dhaka clay for different OCR values. The test results are not corrected with respect to water content. Table 5.2 shows that for each OCR value compared with isotropic effective stress, σ_{ps}' of "perfect" samples, the initial effective stress of "tube" samples reduced significantly because of disturbance caused by penetration of tubes. It can be seen from Table 5.2 that depending on area ratio and OCA, initial effective stress decreased by 9.0% to 26.2%, 5.9% to 25.0%, 3.9% to 21.8% and 3.8% to 21.0% for OCR values 1, 2, 5 & 10, respectively.

Reduction in effective stress due to tube sampling disturbance has also been reported for the regional clays of Bangladesh (Siddique and Sarker,1995; Siddique et al., 2000). Siddique and Sarker (1995) reported a reduction in initial effective stress between 19% to 42% in reconstituted normally consolidated Dhaka Clay. Siddique et al., (2000) reported that initial effective stress reduced between 8.6% to 33.7%, 7.3% to 30% and 5.4% to 22.4% in reconstituted normally consolidated three coastal soil samples. Reduction in mean effective stress in reconstituted and natural normally consolidated and overconsolidated soils due to application of tube sampling strains were also reported. (Baligh et al.,1987; Hajj, 1990; Clayton et al., 1992; Geogiannou and Hight, 1994; Hird and Hajj, 1995; Siddique et al., 1999).

Table 5.2 Comparison of Initial Effective Stress of "Tube" Samples with Isotropic Effective Stress of "Perfect" Samples of Dhaka Clay at Different OCR Values.

OCR	Isotropic effective Stress, σ'_{ps} (kPa)	Initial effective Stress, σ'_i (kPa)						
		T1	T2	T3	T4	T5	T6	T7
1	88.7	80.7	78.2	73.8	65.4	76.3	71.7	69.3
2	40.4	38.0	36.8	34.3	30.3	35.5	32.7	31.9
5	15.1	14.5	13.9	13.0	11.8	13.4	12.4	12.0
10	7.2	6.9	6.7	6.2	5.7	6.5	6.0	5.9

5.3.2 STRESS PATHS

Figs. 5.8, 5.9 and 5.10 present the effective stress paths in s′-t′ space for "tube" samples of Dhaka clay for OCR values of 1, 5, and 10 respectively. These figures also show the stress paths of the corresponding "in situ" sample, for comparison with the "tube" samples. It can be seen from Fig. 5.8, that the nature of the effective stress paths of the normally consolidated "tube" samples are markedly different from that of the respective "in situ" samples. Significant difference in effective stress path between normally consolidated "in situ" and "tube" samples has also been reported for the regional clays of Bangladesh (Siddique and Sarker,1995; Siddique et al., 2000). Figs. 5.9 and 5.10 however, show that the nature of the effective stress paths of the overconsolidated "in situ" and "tube" samples are, in general, similar.

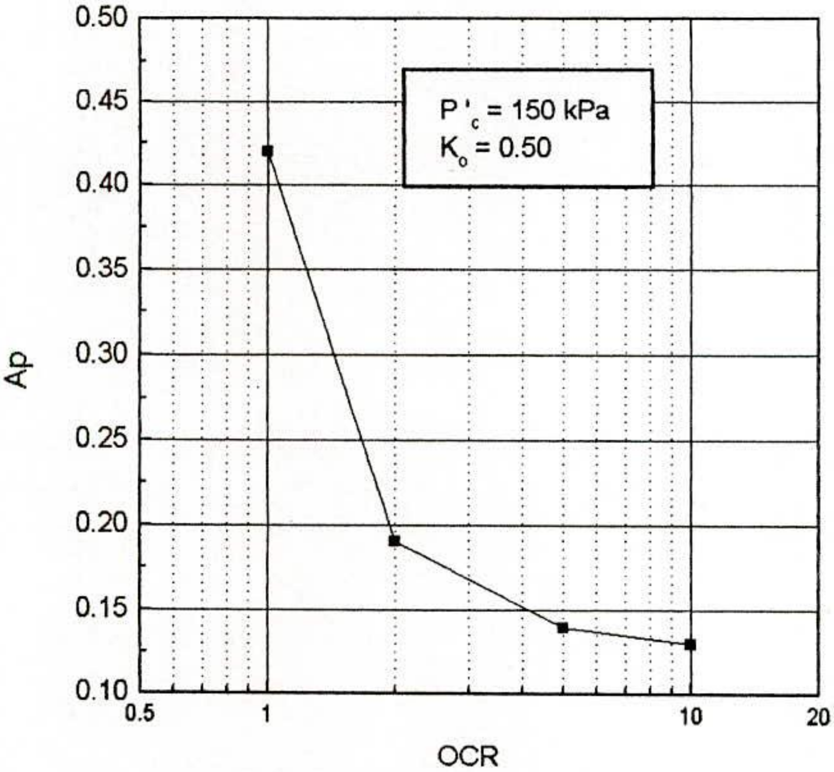


Fig.5.7 Variation of Ap with OCR for "In situ" samples of Dhaka Clay.

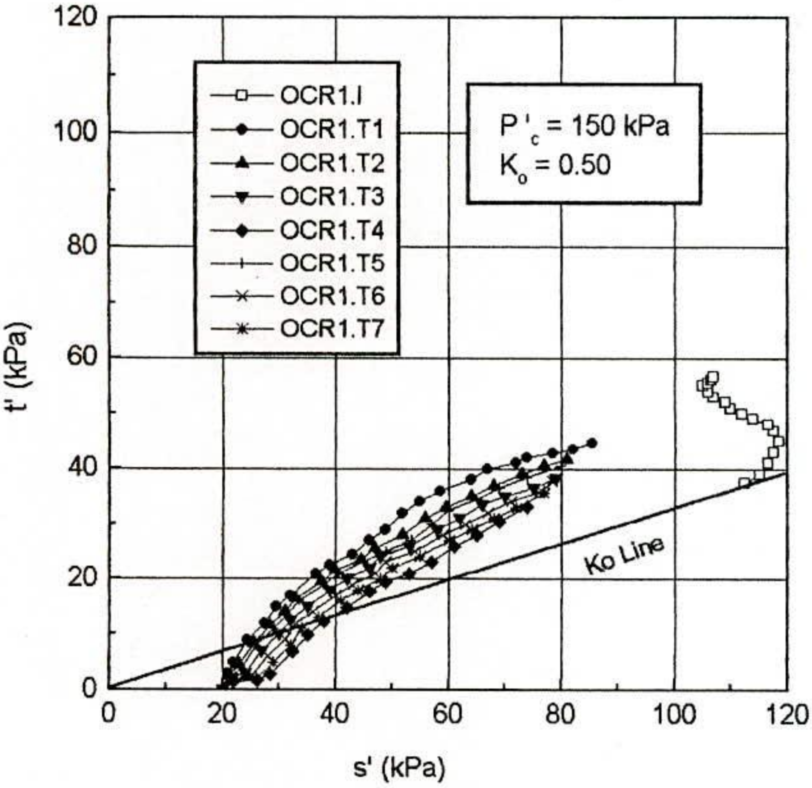


Fig. 5.8. Comparison of effective stress paths for "in situ" and "tube" samples of Dhaka clay for OCR = 1.

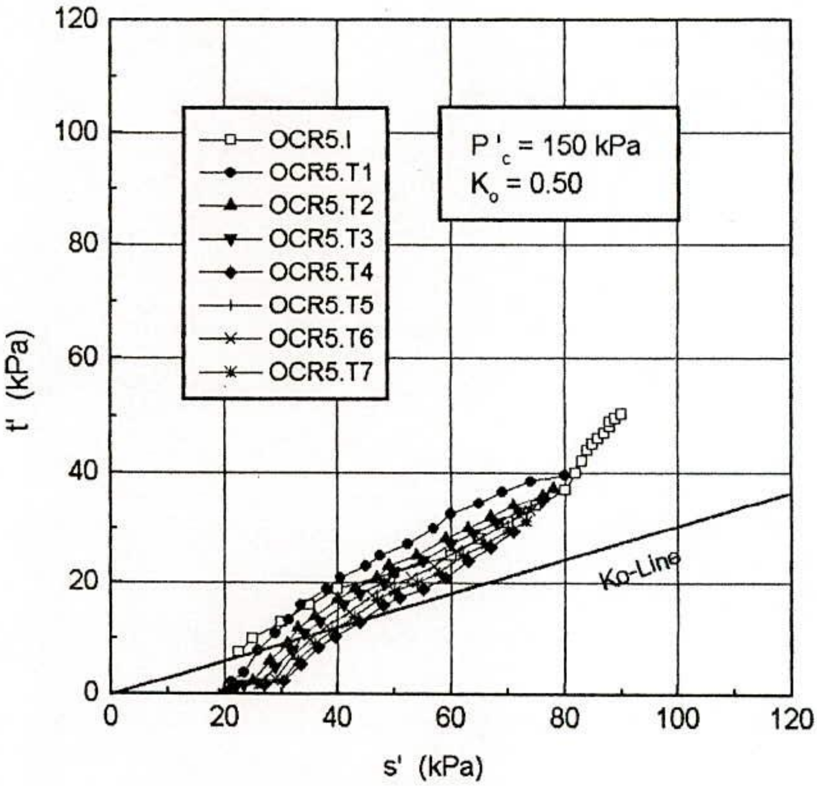


Fig. 5.9. Comparison of effetive stress paths for "in situ" and "tube" samples of Dhaka clay for OCR = 5.

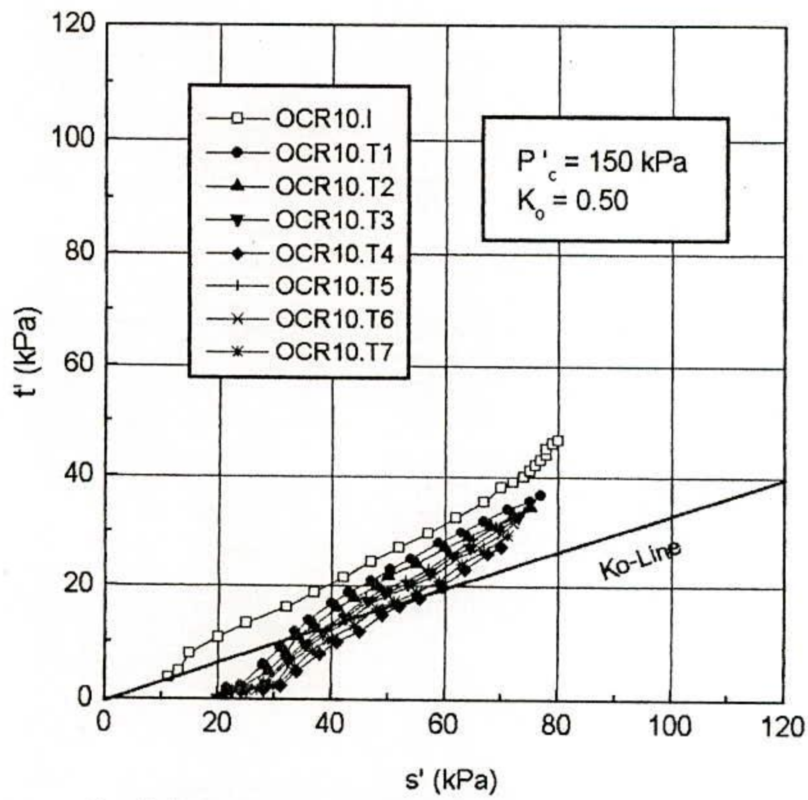


Fig. 5.10. Comparison of effective stress paths for "in situ" and "tube" samples of Dhaka clay for OCR = 10.

5.3.3 STRESS-STRAIN-STRENGTH AND STIFFNESS CHARACTERISTICS

Figs. 5.11, 5.12 and 5.13 present deviator stress versus axial strain plots for "tube" samples of samples of Dhaka clay for OCR values of 1, 5, and 10, respectively. Deviator stress versus axial strain plots of the corresponding "in situ" samples are also shown in Fig. 5.11 to 5.13 for comparison. The following are the main observations:

(1) The peak undrained strength for all "tube" samples are mobilized at relatively larger axial strain than that of "in situ" sample.

(2) Like "in situ" sample, the ultimate strength of "tube" samples are mobilized at larger strain, which are slightly less than that of mobilized at peak. The "tube" samples, therefore, do not show any significant undrained brittleness when sheared in compression.

(3) The stress-strain relationships of the "tube" samples are non-linear.

(4) The nature of stress-strain curves for the "tube" samples are essentially similar to those of "in situ" samples.

The values of undrained shear strength (s_u), axial strain at peak deviator stress (ε_p), initial tangent modulus (E_i), and secant stiffness at half of the peak deviator stress (E_{50}) of the "tube" samples have been determined from the stress-strain data. Tables 5.3, 5.4, 5.5 and 5.6 present the undrained shear characteristics of "tube" samples of Dhaka clay for OCR values of 1, 2, 5, and 10, respectively. The test results are not corrected with respect to water content. It can be seen from Tables 5.3 to 5.6 that for both normally consolidated and overconsolidated "tube" samples, compared with the "in situ" samples, the values of s_u, E_i and E_{50} reduced. The values of ε_p of "tube" samples, however, increased significantly due to disturbance caused by penetration of sampler. Similar effects have also been reported for normally consolidated clay by Okumura (1971), Siddique and Sarker (1995), Siddique et, al. (2000), for Honmoku Marine Clay, Dhaka clay and Coastal soils, respectively. It can also be seen from Tables 5.3 to 5.6 that the decrease in values of s_u, E_i, and E_{50} reduced with increasing OCR. Similar effects have been reported by Hopper (1992) and Hajj (1990) for overconsolidated London clay (OCR = 3.7) and Kaolin clay (OCR = 4), respectively.

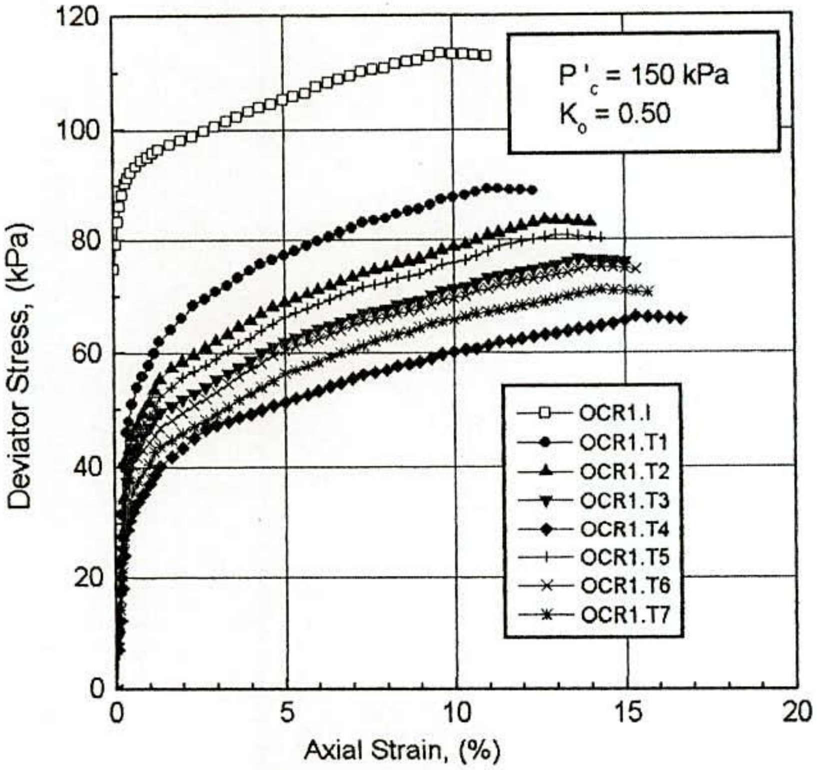


Fig 5.11. Comparison of deviator stress vs. axial strain for "in situ" and "tube" samples of Dhaka clay for OCR = 1.

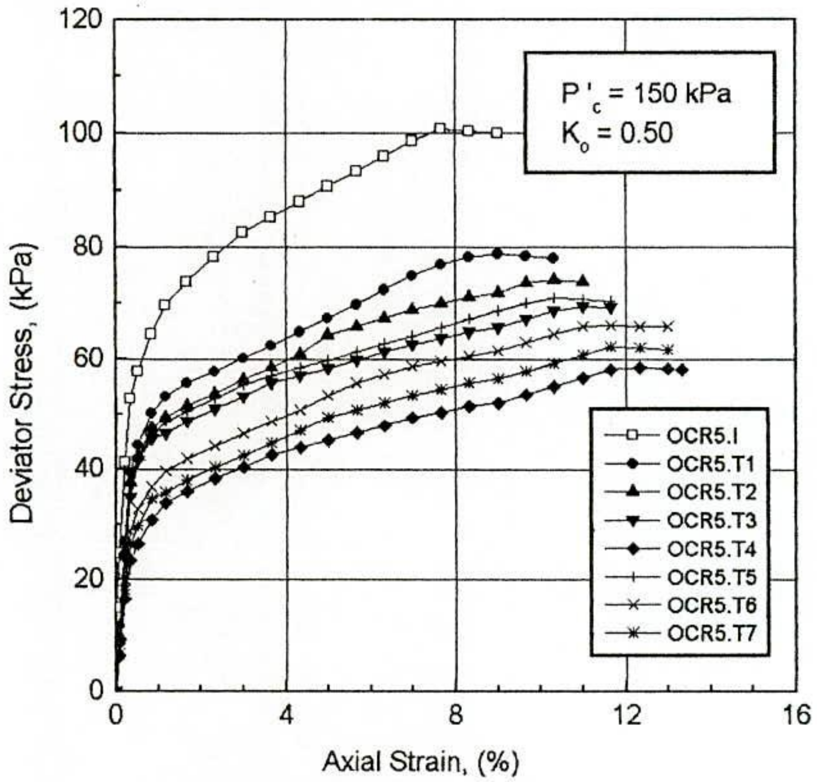


Fig. 5. 12. Comparison of deviator stress vs. axial strain for "in situ" and "tube" samples of Dhaka clay for OCR = 5.

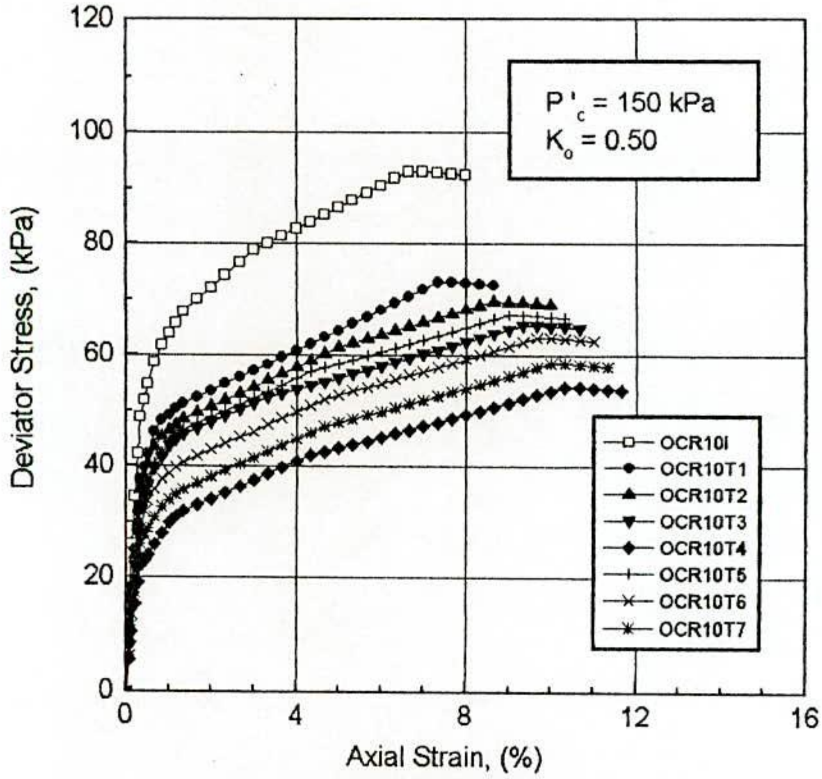


Fig. 5.13. Comparison of deviator stress vs. axial strain for "in situ" and "tube" samples of Dhaka clay for OCR=10

Table 5.3. Comparison of Undrained Shear Properties of "Tube" Samples for Dhaka Clay at OCR = 1.

Sample Designation	s_u (kPa)	ε_p (%)	E_i (kPa)	E_{50} (kPa)	A_p
OCR_1-T1	44.2	11.0	19360	15280	-0.175
OCR_1-T2	41.7	12.6	16490	12520	-0.176
OCR_1-T3	38.3	13.6	14340	10960	-0.178
OCR_1-T4	32.4	15.3	10760	8060	-0.181
OCR_1-T5	40.4	13.0	15060	11510	-0.177
OCR_1-T6	37.6	14.0	13630	9760	-0.179
OCR_1-T7	35.4	14.3	11470	8880	-0.181

Table 5.4. Comparison of Undrained Shear Properties of "Tube" Samples for Dhaka Clay at OCR = 2.

Sample Designation	s_u (kPa)	ε_p (%)	E_i (kPa)	E_{50} (kPa)	A_p
OCR_2-T1	42.6	10.0	18650	14220	-0.162
OCR_2-T2	39.8	11.6	15780	11940	-0.163
OCR_2-T3	37.1	12.7	13630	10650	-0.166
OCR_2-T4	31.1	13.8	10040	7480	-0.176
OCR_2-T5	38.6	12.3	14340	11510	-0.164
OCR_2-T6	35.8	13.0	12550	9500	-0.168
OCR_2-T7	33.2	13.6	10760	8630	-0.173

Table 5.5. Comparison of Undrained Shear Properties of "Tube" Samples for Dhaka Clay at OCR = 5.

Sample Designation	s_u (kPa)	ε_p (%)	E_i (kPa)	E_{50} (kPa)	A_p
OCR_5-T1	39.6	8.9	17210	13100	-0.142
OCR_5-T2	37.2	10.3	14340	11230	-0.145
OCR_5-T3	34.8	11.0	12910	9940	-0.148
OCR_5-T4	29.3	12.3	9320	7050	-0.153
OCR_5-T5	35.5	10.3	13630	10650	-0.147
OCR_5-T6	33.1	11.6	11470	8630	-0.149
OCR_5-T7	31.3	11.6	10140	7910	-0.150

Table 5.6. Comparison of Undrained Shear Properties of "Tube" Samples for Dhaka Clay at OCR = 10.

Sample Designation	s_u (kPa)	ε_p (%)	E_i (kPa)	E_{50} (kPa)	A_p
OCR_{10}-T1	36.7	7.3	15780	12520	- 0.103
OCR_{10}-T2	34.4	8.7	13630	10650	- 0.112
OCR_{10}-T3	32.7	9.3	12200	9780	- 0.113
OCR_{10}-T4	27.2	10.1	8610	6680	- 0.119
OCR_{10}-T5	33.6	9.0	12910	10070	- 0.115
OCR_{10}-T6	31.5	9.7	10760	8350	- 0.117
OCR_{10}-T7	29.3	10.0	9320	7780	- 0.116

Figs. 5.14, 5.15 and 5.16 present secant stiffness versus axial strain plots of "tube" samples of Dhaka clay for OCR values of 1, 5, and 10, respectively. The corresponding plots for the "in situ" samples are also shown in Figs. 5.14 to 5.16 for comparison. It can be seen that similar to "in situ" sample the stiffness of "tube" samples reduce with increase in strain levels. It can also be observed from Tables 5.3 to 5.6 that because of disturbance due to tube sampling, the values of E_i and E_{50} of the "tube" samples decreased for all OCR values. Compared with the "in situ" sample, significant reduction in stiffness for soft normally consolidated Dhaka clay (Siddique and Sarker, 1995) and soft normally consolidated Coastal soils (Siddique et al., 2000) have also been reported. Considerable reduction in stiffness for reconstituted and intact clays due to application of tube sampling strains (Baligh et al., 1985) have also been reported (Baligh et al., 1987; Lacasse and Berre, 1988; Hajj, 1990; Hopper, 1992; Siddique and Clayton, 1995; Siddique et al., 1999).

5.3.4 PORE PRESSURE RESPONSE

Figs. 5.17, 5.18 and 5.19 show the plots of change in pore pressure during shearing against axial strain for "tube" samples of Dhaka clay for OCR values of 1, 5, and 10, respectively. The corresponding plots for the "in situ" samples are also shown in there for comparison. It can be seen from Figs 5.17 to 5.19 that compared with the "in situ" sample, the changes in pore pressure of the normally consolidated and overconsolidated "tube" samples are considerably less. For the normally consolidated and overconsolidated "tube" samples, the pore pressure change increased up to strain about 3% and then reduced sharply up to strain at failure. For both the normally consolidated and overconsolidated "tube" samples, the pore pressure changes are negative at peak deviator stress. Similar pore pressure responses in reconstituted soft normally consolidated "in situ" and "tube" samples of Dhaka clay (Sarker, 1994) and Coastal soils (Farooq,1995) were repoted.

Skempton's pore pressure parameter A at peak deviator stress (A_p) of the "tube" samples have been determined. The values of A_p of the "tube" samples are also shown in Tables 5.3 to 5.6 and it can be seen from these tables that the values of A_p "tube" samples of Dhaka clay are negative for all OCR values. Siddique and Sarker (1995) and Siddique et al. (2000) also found negative

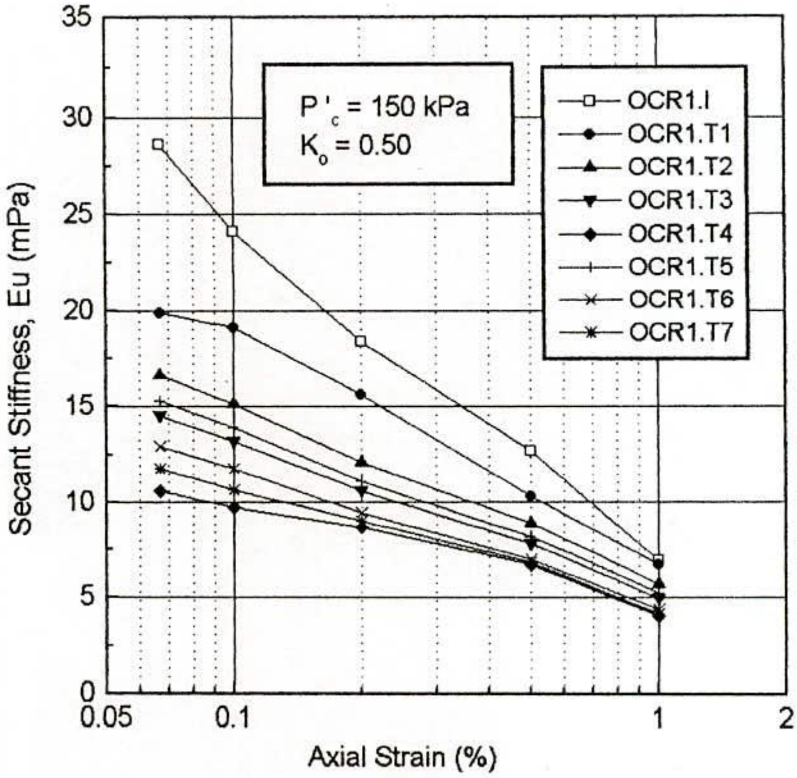


Fig.5.14 Secant stiffness vs. axial strain plots on "in itu" and "tube" samples of Dhaka clay for OCR = 1.

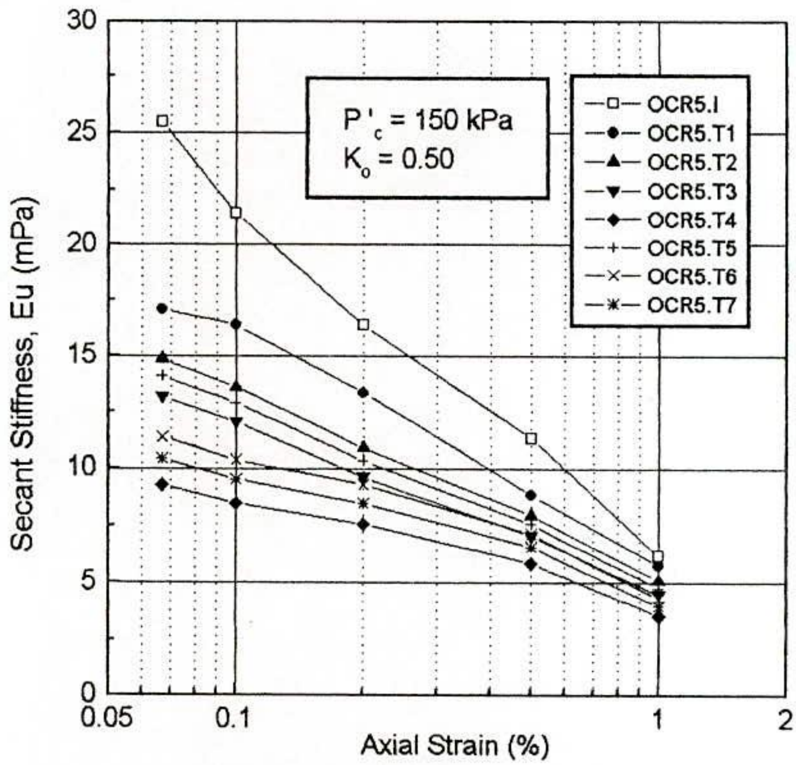


Fig.5.15. Secant stiffness Vs. aixal strain plots on "in situ" and "tube" Samples of Dhaka clay for OCR = 5.

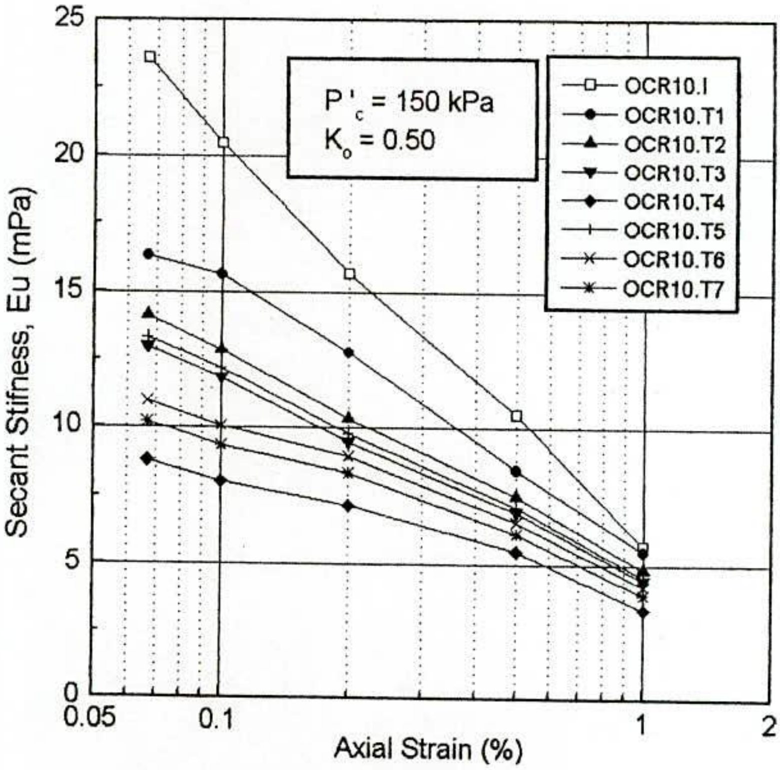


Fig.5.16 Secant stiffness vs. axial strain plots on "in situ" and "tube" Samples of Dhaka for OCR = 10.

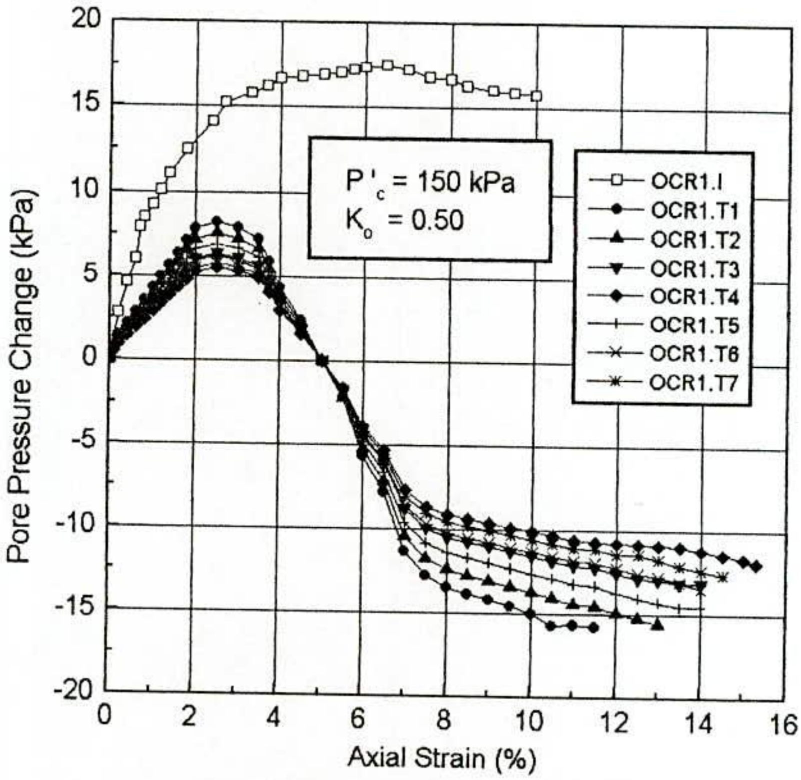


Fig.5.17. Comparison of pore pressure response between "in situ" and "tube" samples of Dhaka clay for OCR = 1.

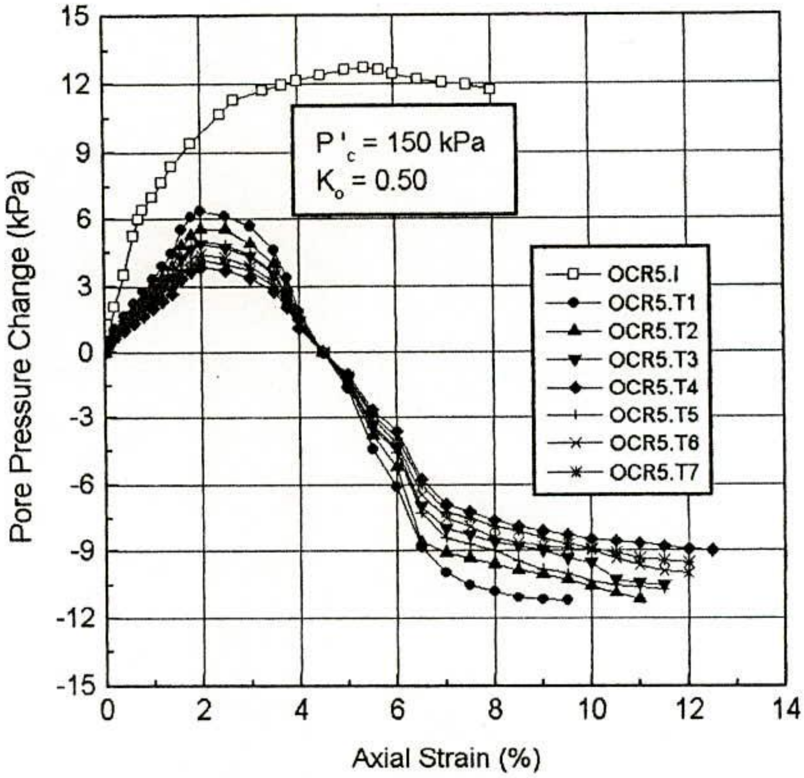


Fig.5.18. Comparison of pore pressures response between "in situ" and "tube" samples of Dhaka Clay for OCR = 5.

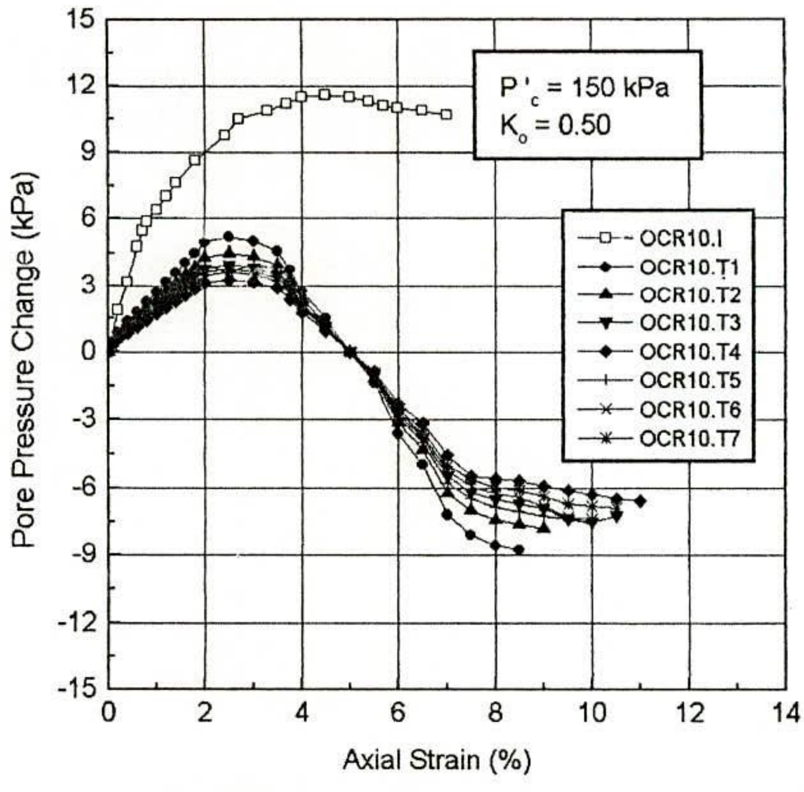


Fig.5.19. Comparison of pore pressure response between "in situ" and "tube" samples of Dhaka clay for OCR = 10.

A_p values for the "tube" samples of normally consolidated soft Dhaka clay and three soft coastal soils, respectively.

5.4 INFLUENCE OF STRESS HISTORY ON TUBE SAMPLING DISTURBANCE EFFECTS

The extent of disturbance due to tube sampling in Dhaka clay has been found to depend on stress history (normally consolidated and overconsolidated) of the samples. Percent reduction in initial effective stresses (σ'_i) of normally consolidated and overconsolidated "tube" samples is presented in Table 5.7. It can be seen that from Table 5.7 that for "tube" samples obtain with a particular cutting shoe geometry, degree of reduction in initial effective stress decreases with increase in overconsolidation ratio (OCR). Fig. 5.20 shows the plots of reduction in initial effective stress with OCR for three "tube" samples. It can be seen from Fig. 5.20 that the reduction in initial effective stress due to tube sampling reduced with increasing OCR.

Table 5.8 shows a summary of the effects of tube sampling disturbance on the strength ratio, stiffness ratio, ε_p and A_p of normally consolidated and overconsolidated samples of Dhaka clay. It can be seen from Table 5.8 that there is a reduction of s_u/σ'_{vc} and E_i/σ'_{vc} with increasing OCR and reduction in undrained shear strength and stiffness with increasing OCR due to tube sampling disturbance are small. However, significantly increase in the reduction of A_p with increasing OCR is found. It can also be seen from Table 5.8 that the increase in ε_p reduced with increasing OCR due to disturbance caused by tube sampling. Fig. 5.21 shows the plots of reduction in A_p versus OCR for three "tube" samples. It is evident from Fig. 5.21 that reduction in A_p sharply increases with increase in OCR.

Fig. 5.22 presents the effective stress paths in s′-t′ space for "tube" samples retrieved with a particular tube sampler (T4) for normally consolidated and overconsolidated samples of Dhaka clay. The nature of effective stress paths are similar for all OCR values as shown in Fig. 5.22 and it appeared that the OCR has no effect on the effective stress paths of "tube" samples.

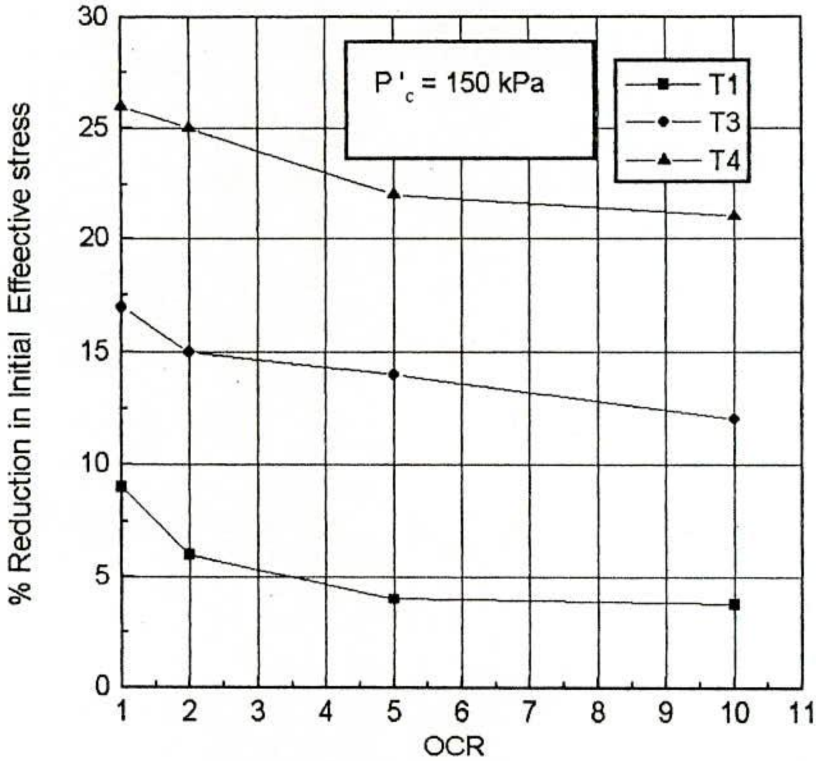


Fig. 20. Variation of %Reduction in Initial Effective Stress with OCR for typical "tube" samples of samplers no. T1, T3 and T4.

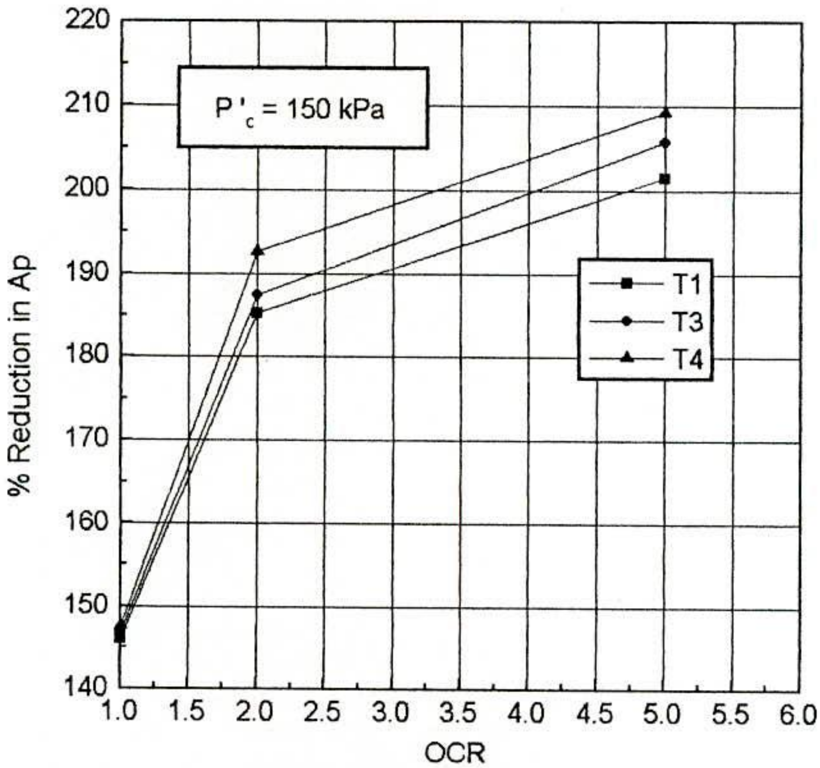


Fig.5.21 Variation of Ap with OCR for typical "tube" samples of Dhaka Clay for samplers no. T1, T3 and T4.

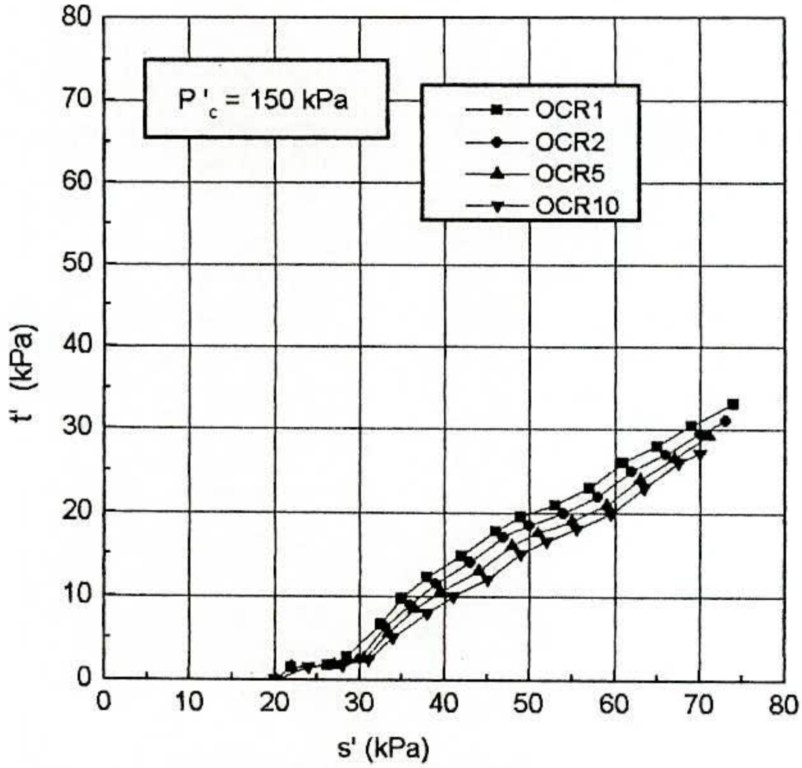


Fig. 5.22. Comparison of effective stress paths at different OCR of Dhaka clay by sampling tube no. T4.

Table 5.7 Reduction in Initial effective stress of "Tube" Samples with Isotropic effective stress of "Perfect" Samples at different OCR values.

OCR Value	Isotropic effective stress, σ'_{ps} (kPa)	% Reduction in σ'_i compared with σ'_{ps}						
		T1	T2	T3	T4	T5	T6	T7
1	88.7	9.0	11.8	16.8	26.2	13.9	19.2	21.9
2	40.4	5.9	8.9	15.0	25.0	12.1	19.0	21.0
5	15.1	3.9	7.8	13.8	21.8	11.1	17.8	20.4
10	7.2	3.8	7.0	12.0	21.0	9.9	15.9	18.0

Table 5.8 Summary of the Influence of OCR on "Tube" Sampling Disturbance Effects

OCR	Change in properties as compared with 'in situ' samples, (%)				
	Reduction in s_u / σ'_{vc}	Increase in ε_p	Reduction in E_i / σ'_{vc}	Reduction in E_{50} / σ'_{vc}	Reduction in A_p
1	22.0 – 43.0	13.4 – 57.7	32.1 – 62.2	33.4 – 64.9	146 – 148
3	21.4 – 42.6	11.1 – 53.3	29.7 – 62.1	30.5 – 63.4	185 – 193
5	21.4 – 41.9	12.1 – 52.6	29.4 – 61.8	35.9 – 65.5	201 – 209
10	21.2 – 41.6	9.0 – 50.7	29.0 – 61.3	33.9 – 64.7	179 – 192

5.5 ASSESSMENT OF EFFECT OF SAMPLER GEOMETRY ON DISTURBANCE OF NORMALLY CONSOLIDATED AND OVERCONSOLITED DHAKA CLAY

Initial effective stress, undrained stress-strain-strength, stiffness and pore pressure parameters of "tube" and "in situ" samples were determined from undrained triaxial compression tests.

The experimentally measured soil parameters of the normally consolidated and overconsolidated "in situ" and "tube" samples have been presented in the previous sections. The effect of sampler geometry on disturbance have been assessed by comparing the soil parameters of the "tube" samples with those of the "in-situ" samples retrieved with samplers of different area ratio, D_e/t ratio and outside cutting edge angle (OCA). Summary of the effects of cutting shoe geometry on the undrained soil parameters of normally consolidated and overconsolidated samples are presented in Tables 5.9, 5.10, 5.11 and 5.12 for Dhaka clay of OCR values of 1, 2, 5, and 10, respectively.

5.5.1 EFFECT OF AREA RATIO AND D_e/t RATIO

The experimentally measured undrained soil parameters of the "tube" samples retrieved with samplers of different area ratio have been compared with those of the "in situ" sample. It has been found that area ratio and D_e/t ratio of a sampler have a profound influence on the measured undrained triaxial shear parameters. Tables 5.9 to 5.12 show that increasing area ratio (or reducing D_e/t ratio) caused increasing reductions in the values of σ'_i , s_u, E_i, E_{50} and A_p. Increasing area ratio (or decreasing D_e/t ratio) of sampler, however, caused an increase in the value of ε_p. Figs. 5.23, 5.24, 5.25 and 5.26 show comparisons of the change in σ'_i, s_u, ε_p, E_i and E_{50} due to change in area ratio of the samplers for Dhaka clay of OCR values of 1, 2, 5, and 10, respectively. Figs. 5.23 to 5.26 show that the values of σ'_i, s_u, E_i and E_{50} reduce with increase in area ratio while the values of ε_p increases with increase in area ratio. Fig.5.27 shows comparison of the percent reduction in A_p due to change in area ratio of the samplers for different OCR values of "tube" samples. The reduction in A_p increases with increase in area ratio.

Figs. 5.28 to 5.32 show comparisons of the change in soil properties due to change in D_e/t ratio of the normally consolidated and overconsolidated "tube" samples for Dhaka clay. The values of σ'_i, s_u, E_i and E_{50}, reduce with decrease in D_e/t ratio while the values of ε_p increases with decrease in D_e / t ratio. Fig. 5.32 show that the reduction in A_p reduces with increase in D_e/t ratio.

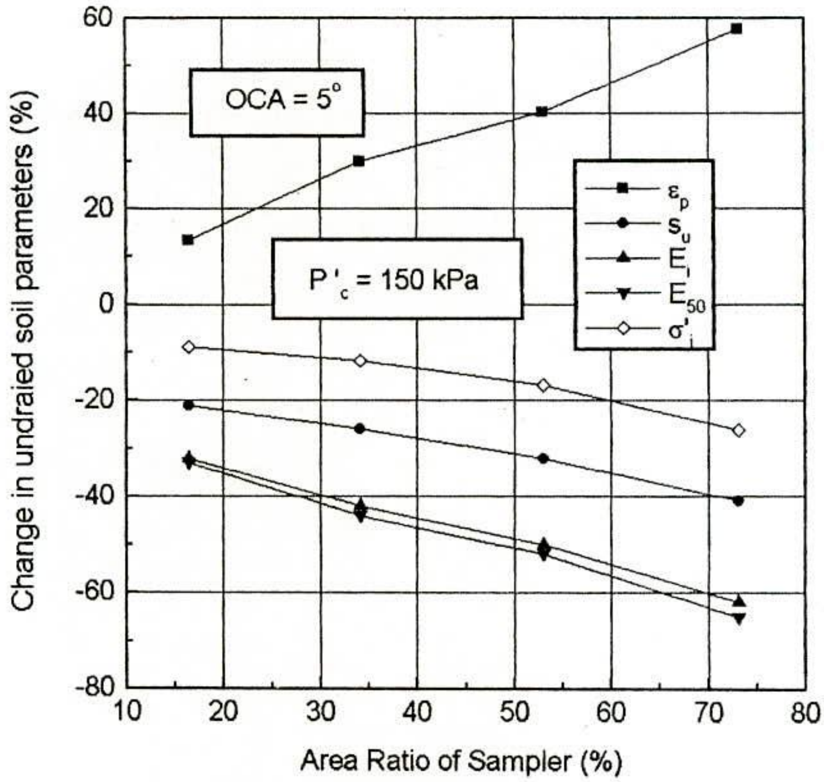


Fig. 5.23 Infuence of area ratio of samles on undrained soil parameters for samples of Dhaka Clay for OCR = 1

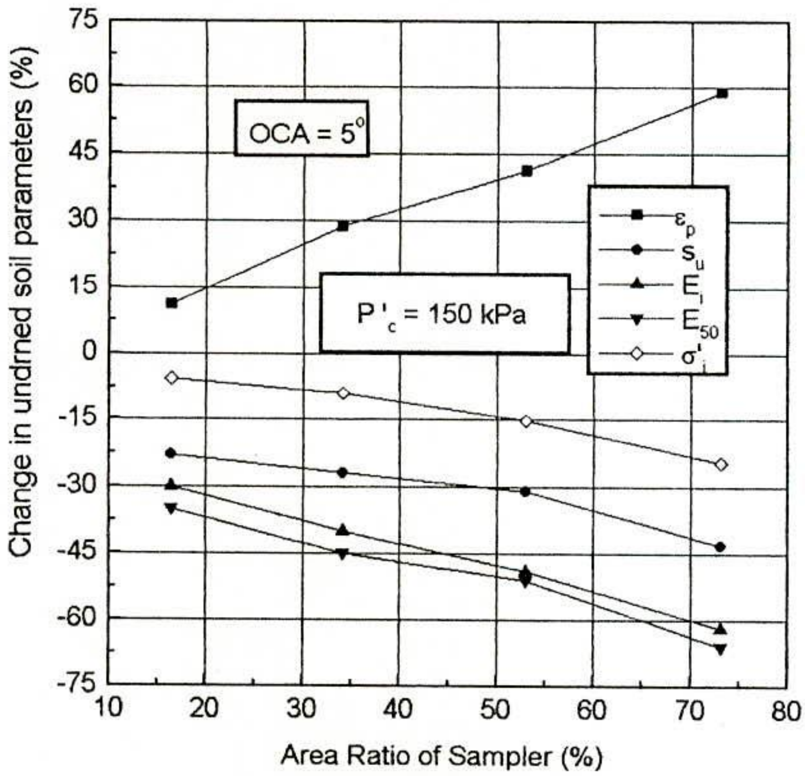


Fig.5.24. Influence of area ratio of samplers on undrained soil parameters for samples of Dhaka Clay for OCR = 2.

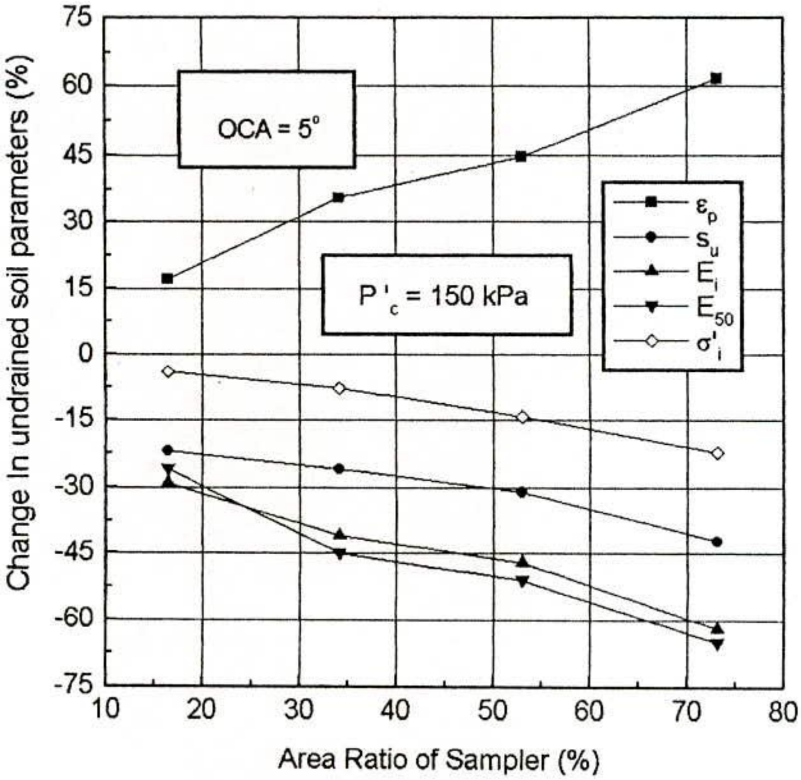


Fig.5.25. Infuence of area ratio of samplers on undrained soil parameters for samples of Dhaka Clay for OCR = 5.

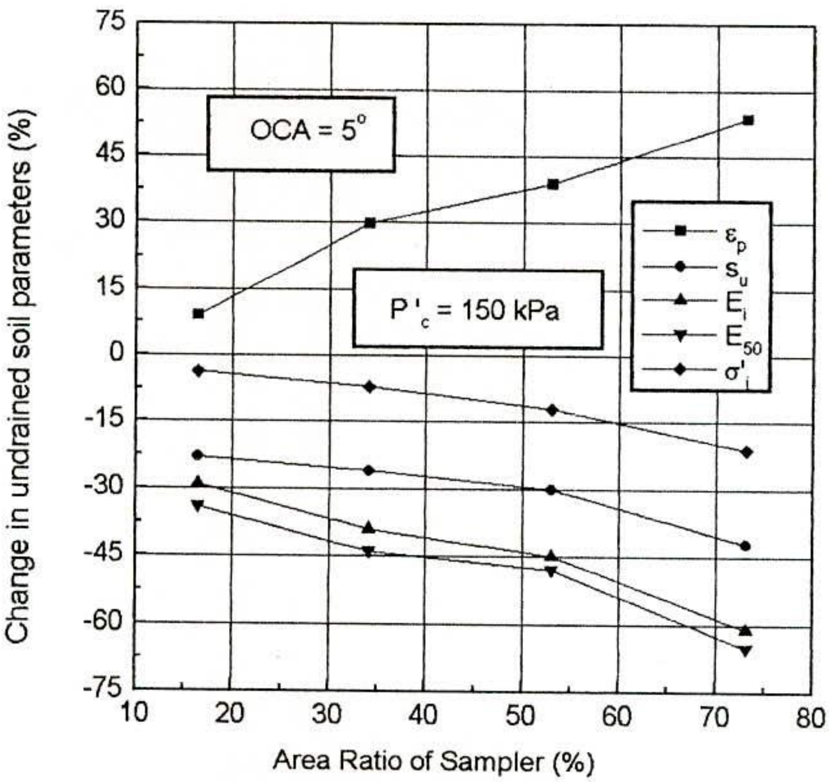


Fig.5.26 Infuence of area ratio of samplers on undrained soil parameters for samples of Dhaka clay for OCR = 10.

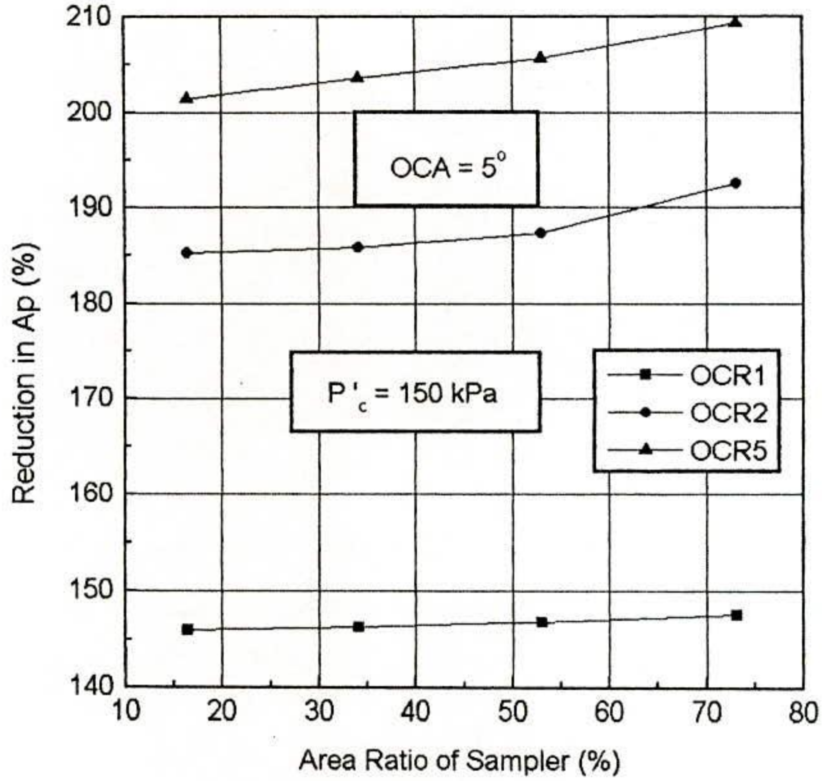


Fig.5.27 Influence of area ratio of samplers on Ap for samples of different OCR.

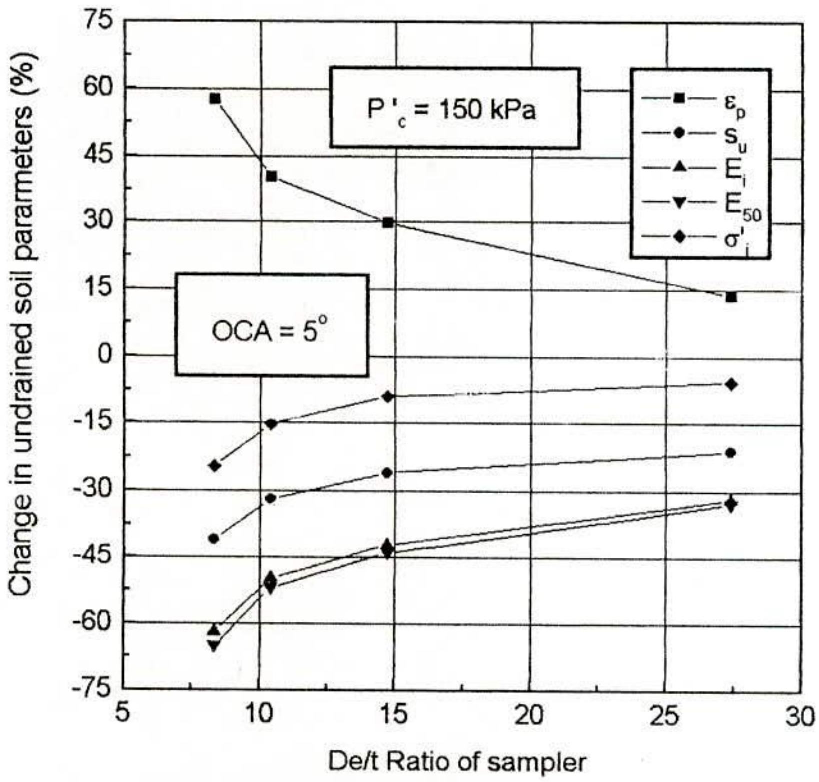


Fig.5.28 Influence of De/t ratio of samples on undrained soil parameters for samples of Dhaka clay OCR = 1.

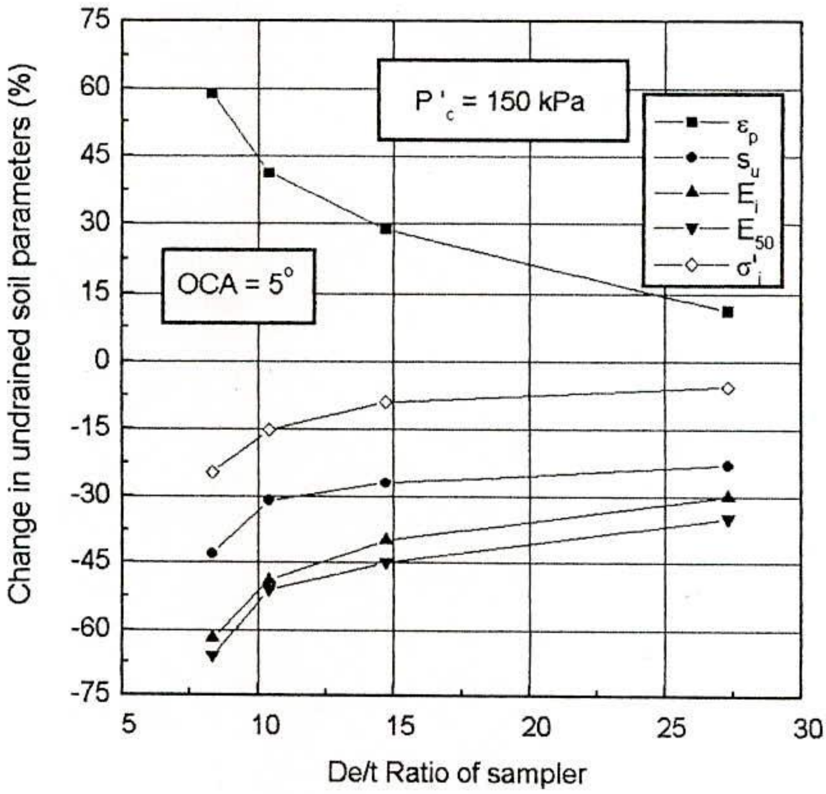


Fig.5.29. Infuence of De/t ratio sampler on undrained soil parmeters for samples of Dhaka clay for OCR =2.

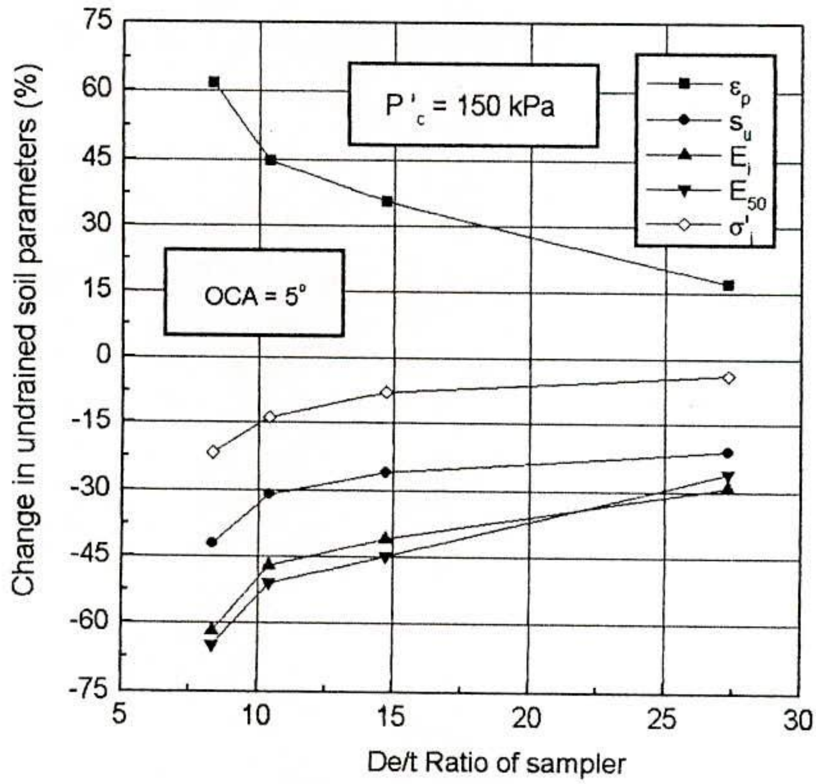


Fig.5.30 Influence of De/t ratio of samplers on undrained soil parameters for samples of Dhaka Clay for OCR =5.

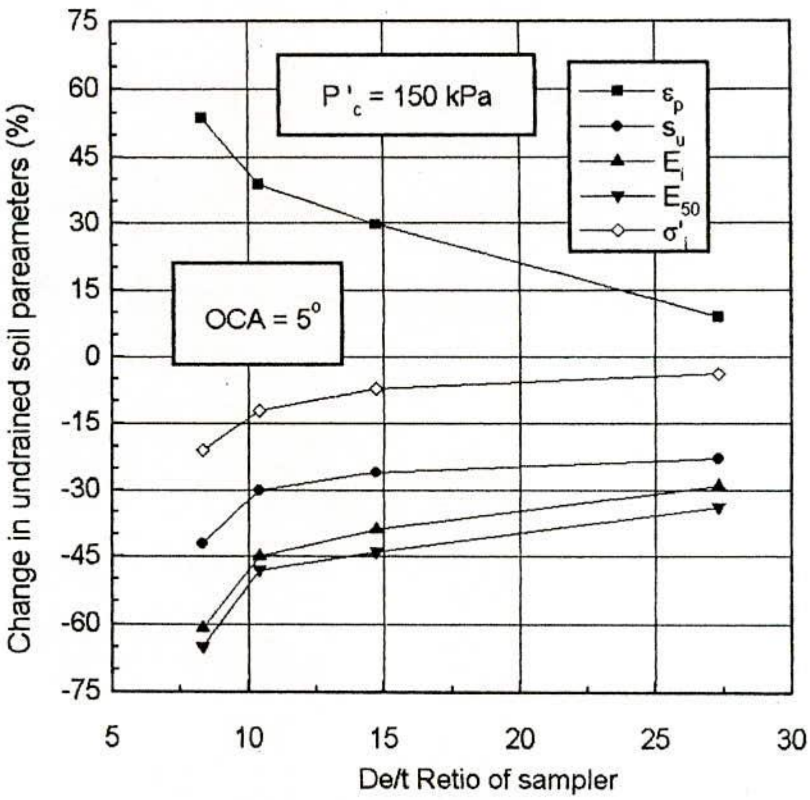


Fig.5.31 Infuence of De/t ratio of samplers on undrained soil parameters for samples of Dhaka Clay for OCR = 10.

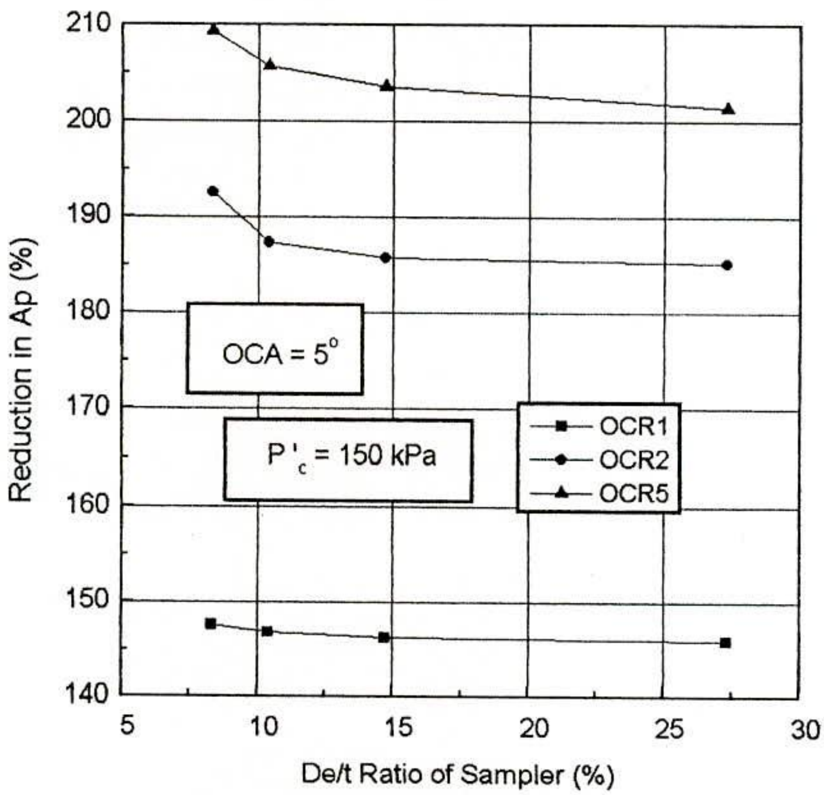


Fig.5.32 Infuence of De/t ratio of samplers on Ap for samples of different OCR.

Table 5.9 Summary of the effects of Cutting Shoe geometry on Soil Parameters for "Tube" Samples of Dhaka Clay at OCR = 1.

Sample Designa-tion	Tube Sampler Dimensions			%Change in properties compared with 'in-situ' sample					
	Area Ratio (%)	D_e / t Ratio	OCA (°)	Reduc-tion in σ'_i	Reduc-tion in s_u	Increa-se in ε_p	Reduc-tion in E_i	Reduc-tion in E_{50}	Reduc-tion in A_p
OCR_1-T1	16.4	27.3	5	9.0	22	13.4	32	33	146.0
OCR_1-T2	34.1	14.7	5	11.8	26	29.9	42	45	146.3
OCR_1-T3	53.0	10.4	5	16.8	32	40.2	50	52	146.8
OCR_1-T4	73.1	8.3	5	26.2	43	57.7	62	65	147.6
OCR_1-T5	34.1	14.7	10	13.9	29	34.0	47	50	146.6
OCR_1-T6	34.1	14.7	15	19.2	33	44.3	51	57	147.1
OCR_1-T7	34.1	14.7	20	21.9	37	47.4	60	61	147.6

Table 5.10 Summary of the effects of Cutting Shoe geometry on Soil Parameters for "Tube" Samples of Dhaka Clay at OCR = 2.

Sample Designa-tion	Tube Sampler Dimensions			%Change in properties compared with 'in-situ' sample					
	Area Ratio (%)	D_e / t Ratio	OCA (°)	Reduc-tion in σ'_i	Reduc-tion in s_u	Increa-se in ε_p	Reduc-tion in E_i	Reduc-tion in E_{50}	Reduc-tion in A_p
OCR_2-T1	16.4	27.3	5	5.9	23	11.1	30	35	185.3
OCR_2-T2	34.1	14.7	5	8.9	27	28.9	40	45	185.8
OCR_2-T3	53.0	10.4	5	15.1	31	41.1	49	51	187.4
OCR_2-T4	73.1	8.3	5	25.0	43	53.3	62	66	192.6
OCR_2-T5	34.1	14.7	10	12.1	29	36.7	46	47	186.3
OCR_2-T6	34.1	14.7	15	19.1	34	44.4	53	56	188.4
OCR_2-T7	34.1	14.7	20	21.0	39	51.1	59	60	191.1

Table 5.11 Summary of the effects of Cutting Shoe geometry on Soil Parameters for "Tube" Samples of Dhaka Clay at OCR = 5.

Sample Designa-tion	Tube Sampler Dimensions			%Change in properties compared with 'in-situ' sample					
	Area Ratio (%)	D_e / t Ratio	OCA (^{o})	Reduc-tion in σ'_i	Reduc-tion in s_u	Increa-se in ε_p	Reduc-tion in E_i	Reduc-tion in E_{50}	Reduc-tion in A_p
OCR_5-T1	16.4	27.3	5	3.9	22	17.1	29	36	201.4
OCR_5-T2	34.1	14.7	5	7.8	26	35.5	41	45	203.6
OCR_5-T3	53.0	10.4	5	13.8	31	44.7	47	51	205.7
OCR_5-T4	73.1	8.3	5	21.8	42	51.8	62	66	209.3
OCR_5-T5	34.1	14.7	10	11.1	30	35.5	44	48	205.0
OCR_5-T6	34.1	14.7	15	17.8	34	52.6	53	58	206.4
OCR_5-T7	34.1	14.7	20	20.4	38	52.6	58	61	207.1

Table 5.12 Summary of the effects of Cutting Shoe geometry on Soil Parameters for "Tube" Samples of Dhaka Clay at OCR = 10.

Sample Designa-tion	Tube Sampler Dimensions			%Change in properties compared with 'in-situ' sample					
	Area Ratio (%)	D_e / t Ratio	OCA (^{o})	Reduc-tion in σ'_i	Reduc-tion in s_u	Increa-se in ε_p	Reduc-tion in E_i	Reduc-tion in E_{50}	Reduc-tion in A_p
OCR_{10}-T1	16.4	27.3	5	3.8	23	9.0	29	34	179.2
OCR_{10}-T2	34.1	14.7	5	7.0	26	29.9	39	44	186.2
OCR_{10}-T3	53.0	10.4	5	12.0	30	38.8	45	48	186.9
OCR_{10}-T4	73.1	8.3	5	21.0	42	50.7	61	65	191.5
OCR_{10}-T5	34.1	14.7	10	9.9	28	34.3	42	47	188.5
OCR_{10}-T6	34.1	14.7	15	15.9	32	44.8	51	56	190.0
OCR_{10}-T7	34.1	14.7	20	18.0	37	49.2	58	59	189.2

Compared with the "in situ" sample, the following effects on the measured soil parameters for normally consolidated and overconsolidated Dhaka clay have been observed due to increase in area ratio from 16.4% to 73.1% (or decrease in D_e/t ratio from 27.3 to 8.3) of samplers:

(1) Initial effective stress, σ'_i reduced by 9.0 to 26.2%, 5.9 to 25.0%, 3.9 to 21.8% and 3.8 to 21.0% for OCR values of 1, 2, 5, and 10, respectively.

(2) Values of s_u decreased by 22% to 43%, 23% to 43%, 22% to 42% and 23% to 42% for OCR values of 1, 2, 5, and 10, respectively.

(3) Values of ε_p increased by 13.4% to 57.7%, 11% to 53.3%, 17.1% to 51.8% and 9.0% to 50.7% for OCR values of 1, 2, 5, and 10, respectively.

(4) Values of E_i reduced by 32% to 62%, 30% to 62%, 29% to 62% and 29% to 61% for OCR values of 1, 2, 5, and 10, respectively.

(5) Values of E_{50} reduced by 33% to 65%, 35% to 66%, 36% to 66% and 34% to 65% for OCR values of 1, 2, 5, and 10, respectively.

(6) Values of A_p reduced by 146.0% to 147.6%, 185.3% to 192.6%, 201.4% to 209.3% and 179.2% to 191.5% for OCR values of 1, 2, 5, and 10, respectively.

Siddique and Sarker (1996) and Siddique et al. (2000) investigated the effect of area ratio on soil parameters of reconstituted normally consolidated soft Dhaka clay and Chittagong coastal soils, respectively. Siddique and Sarker (1996) reported reduction in σ'_i (up`to 42%), s_u (up to 35%) and E_i (up to 49%) and an increase in ε_p (up to 81%) in reconstituted normally consolidated soft Dhaka clay due to increase in area ratio of samplers from 10.8% to 55.2%. For "tube" samples retrieved with tube having equivalent cutting shoe design (AR = 34.1%, D_e/t = 14.7), it has been observed that the reduction in σ'_i, s_u, E_i and E_{50} for reconstituted normally consolidated soft Dhaka clay (Siddique and Sarker, 1996) are greater than those of the firm Dhaka clay samples used in this investigation. Due to increase in area ratio, Siddique et al. (2000) also reported that significant, the values of σ'_i, s_u and E_i reduced while, the value of ε_p increased of reconstituted normally consolidated soft samples of three Chittagong coastal soils.

5.5.2 EFFECT OF OUTSIDE CUTTING EDGE ANGLE

The experimentally measured undrained soil parameters of the "tube" samples retrieved with samplers of different outside cutting edge angle (OCA) have been compared with those of the "in situ" samples. It has been found that OCA of a sampler has a marked influence on the measured undrained triaxial shear parameters. Increasing OCA caused increasing reductions in σ'_i, s_u, E_i, E_{50} and A_p. Increasing OCA of sampler, however, caused an increase in ε_p. Figs. 5.33 to 5.37 show comparisons of the change in soil properties due to change in OCA of the samplers for the normally consolidated and overconsolidated samples Dhaka clay. From Figs. 5.33 to 5.36, it can be seen that values of σ'_i, s_u, E_i and E_{50} reduce with increase in OCA while the values of ε_p increases with increase in OCA. Figs.5.37 shows that reduction in A_p increases with increase in OCA.

Compared with the "in situ" sample, the following changes on the soil parameters of the normally consolidated and overconsolidated Dhaka clay have been observed due to increase in OCA from 5° to 20°:

(1) Initial effective stress reduced by 11.8 to 21.9%, 8.9 to 21.0%, 7.8 to 20.4% and 7.0 to 18.0% for OCR values of 1, 2, 5, and 10, respectively.

(2) Values of s_u reduced by 26% to 37%, 27% to 39%, 26% to 38% and 26% to 37% for OCR values of 1, 2, 5, and 10, respectively.

(3) Values of ε_p increased by 29.9% to 47.4%, 28.9% to 51.1%, 35.5% to 52.6% and 29.9% to 49.2% for OCR values of 1, 2, 5, and 10, respectively.

(4) Values of E_i decreased by 42% to 60%, 40% to 59%, 41% to 58% and 39% to 58% for OCR values of 1, 2, 5, and 10, respectively.

(5) Values of E_{50} decreased by 45% to 61%, 45% to 60%, 45% to 61% and 44% to 59% for OCR values of 1, 2, 5, and 10 respectively.

(6) Values of A_p reduced by 146.3% to 147.6%, 185.8% to 191.1%, 203.6% to 207.1%, and 186.2% to 189.2%, for OCR values of 1, 2, 5, and 10, respectively.

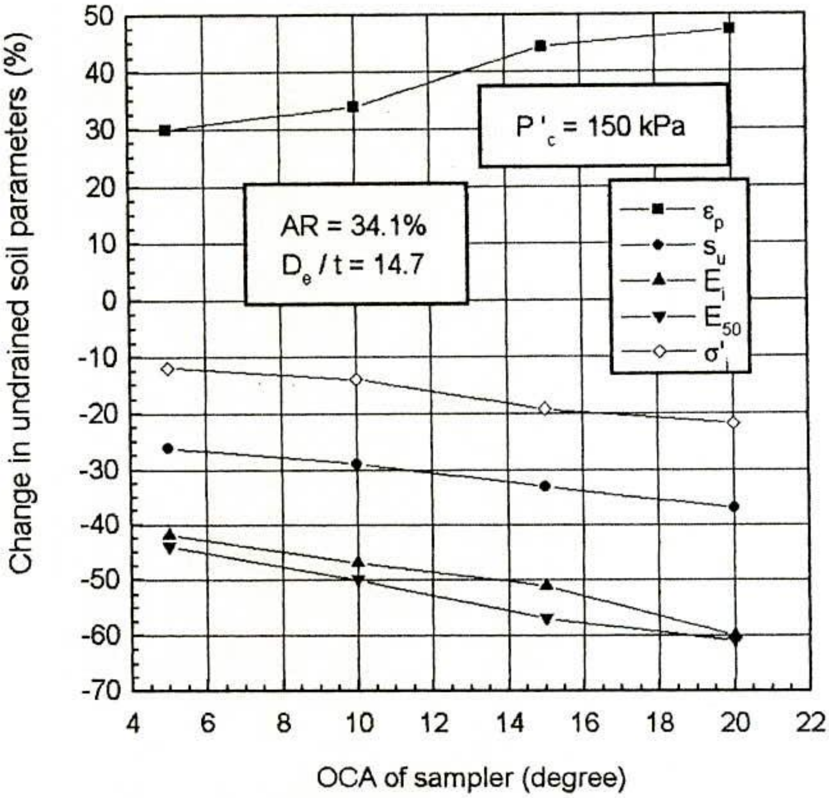


Fig.5.33 Influence of OCA of samplers (degree) on undrained soil parameters for samples of Dhaka Clay for OCR = 1.

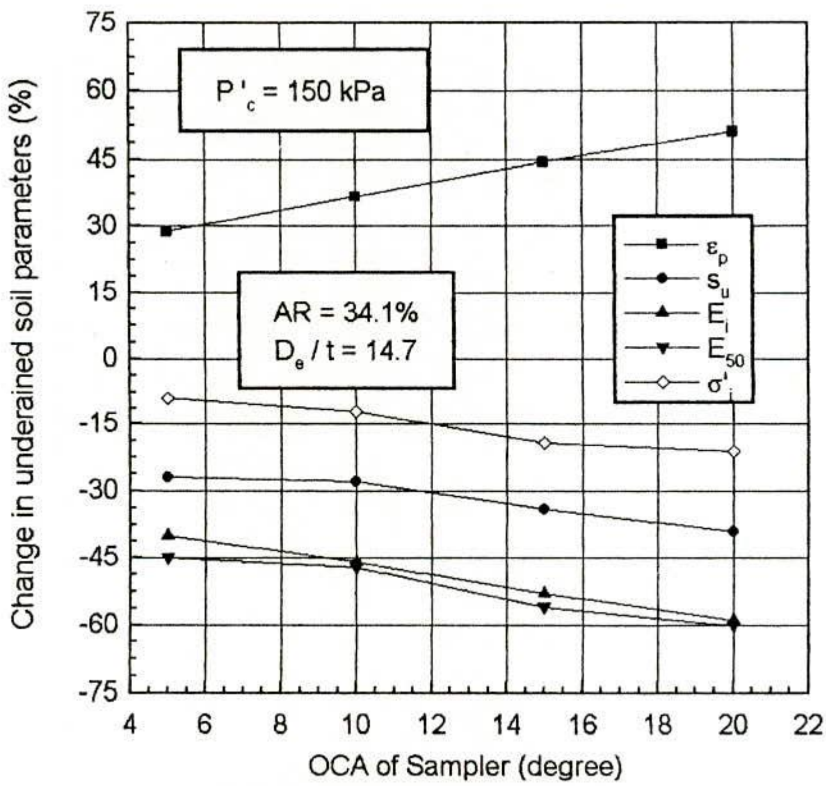


Fig.5.34 Influence of OCA for samplers (degree) on undrained soil parameters for samples of Dhaka Clay for OCR = 2.

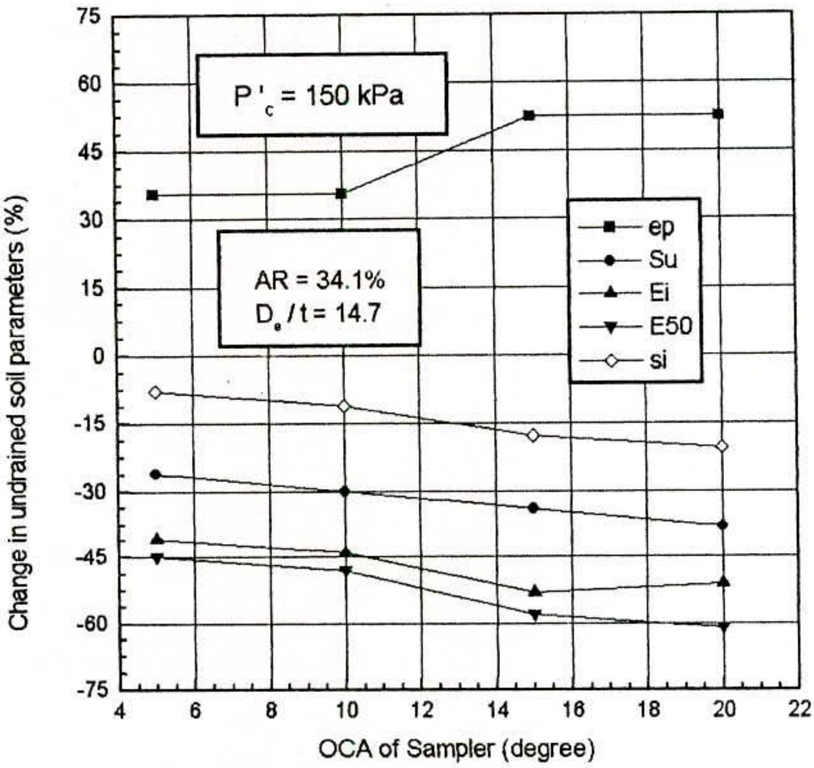


Fig. 5.35 Influence of OCA of samplers (degree) on undriained soil parameters for samples of Dhaka Clay for OCR = 5.

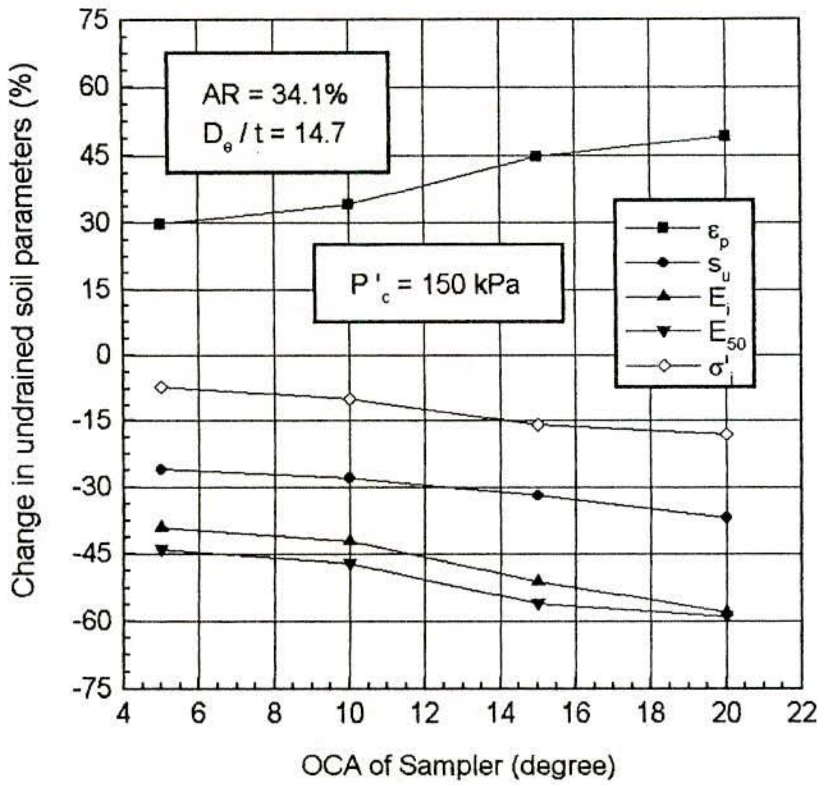


Fig.5.36 Influence of OCA of samplers (degree) on undrained soil parameters for samples of Dhaka Clay for OCR = 10.

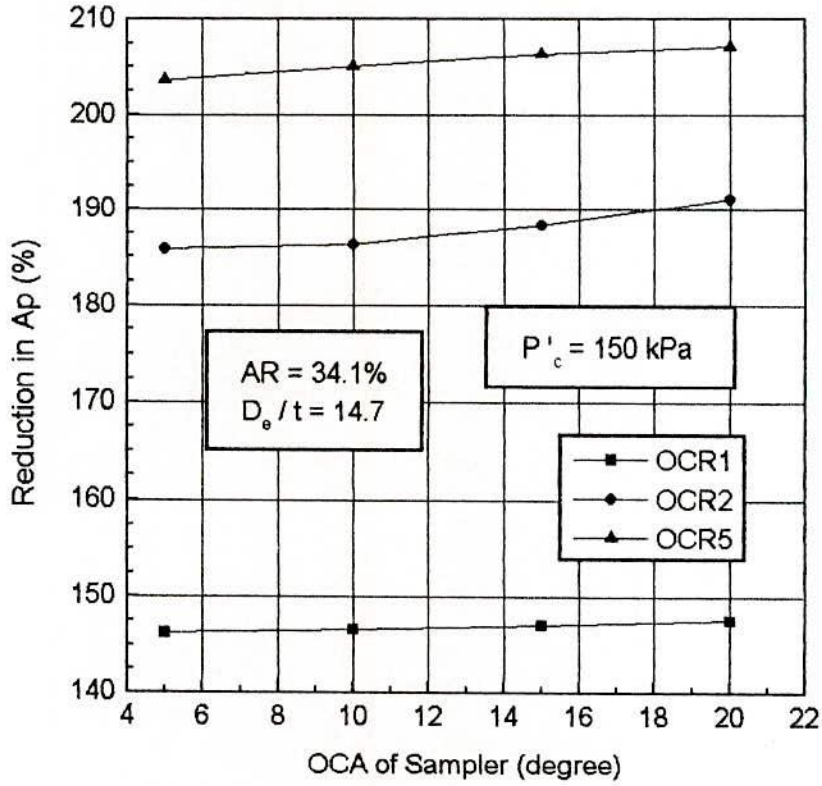


Fig.5.37 Influence of OCA of samplers (degree) on Ap for samples of different OCR.

Siddique and Sarker (1996) reported reduction in s_u and E_i of up to 32% and 41%, respectively, while, an increase in ε_p of up to 81%, due to increase in OCA from 4° to 15° in reconstituted normally consolidated soft Dhaka clay. Siddique and Sarker (1996) also reported that the values of A_p and σ'_i reduced considerably due to increase in OCA. Siddique and Farooq (1998) reported significant reduction in σ'_i, E_i and marked increase in ε_p due to increase in OCA from 4° to 15° in a reconstituted normally consolidated soft Chittagong coastal soil.

From the above findings, it is evident that for good quality sampling, a sampler ought to have a well combination of area ratio, D_e/t ratio and OCA. In order to minimize disturbance due to sampling in firm Dhaka clay for OCR values of 1, 2, 5, and 10, area ratio and outside cutting edge angle of sampler should be kept as low as possible. From practical point of view the area ratio of a tube sampler should not exceed 10% and the outside cutting edge of a tube sampler should preferably be less than 5°.

5.6 ASSESSMENT OF DEGREE OF DISTURBANCE IN "TUBE" SAMPLES

Degree of disturbance can be assessed by investigating the behaviour of the least disturbed sample which is usually a laboratory simulated "perfect" sample. Because of additional disturbances other than that occurred due to total stress release, the residual effective stress of "tube" sample, σ_i' is usually less than the isotropic effective stress, σ_{ps}' of a "perfect" sample. Based on the values of σ_{ps}' of "perfect" sample and initial effective stress, σ_i' for "tube" sample, degree of disturbance (D_d) has been calculated using the equation no.-2.9, proposed by Okumura (1971) and Nelson et al. (1971).

The values of degree of disturbance (D_d) of the for the normally consolidated and overconsolidated "tube" samples for Dhaka clay are shown in Table 5.13. It can be seen from Table 5.13 that the values of degree of disturbance varied from 0.09 to 0.26, 0.06 to 0.25, 0.04 to 0.22 and 0.04 to 0.21 for the 'tubes' samples of Dhaka clay for OCR values of 1, 2, 5, and 10, respectively. The degree of disturbance has been plotted against area ratio, D_e/t ratio and outside cutting edge angle (OCA), as shown in Figs. 5.38, 5.39 and 5.40, respectively. It can be seen from Figs. 5.38 and 5.40 that the values of D_d increases with increasing values of area ratio and OCA of sampler. Fig. 5.39 shows that the values of D_d decreases with increasing D_e/t ratio.

The quantitative values of the degree of disturbance have also been found to be dependent on the design parameters of the samplers used for sampling the clays. Values of D_d increased by up to 2.89 times due to increase in area ratio from 16.4% and 73.1% (or decrease in D_e/t ratio from 27.3 to 8.3) for the normally consolidated firm Dhaka clay. For an increase in OCA from 5^0 to 20^0, values of D_d increased by up to 83% for "tube" samples of the normally consolidated firm Dhaka clay. Increase in the values of D_d increases with increasing values of area ratio and OCA has also been reported for reconstituted normally consolidated soft samples of Dhaka clay (Siddique and Sarker, 1996) and soft samples of coastal soils (Siddique and Farooq, 1998; Siddique et al. 2000).

Marked increase in the degree of disturbance (measured in terms of tube sampling strains) with decreasing D_e/t ratio of sampler has also been analytically predicted (Baligh et al., 1987; Baligh 1985). Clayton et al., (1998) from numerical finite element analyses also predicted considerable increase in the degree of disturbance with increasing area ratio (or decreasing D_e/t ratio) and increasing OCA of sampler.

Table 5.13 Comparison of Degree of Disturbance for "Tube" Samples of Dhaka clay at Different OCR Values.

OCR	Degree of disturbance, D_d						
	T1	T2	T3	T4	T5	T6	T7
1	0.09	0.12	0.17	0.26	0.14	0.19	0.22
2	0.06	0.09	0.15	0.25	0.12	0.19	0.21
5	0.04	0.08	0.14	0.22	0.11	0.18	0.20
10	0.04	0.07	0.12	0.21	0.10	0.16	0.18

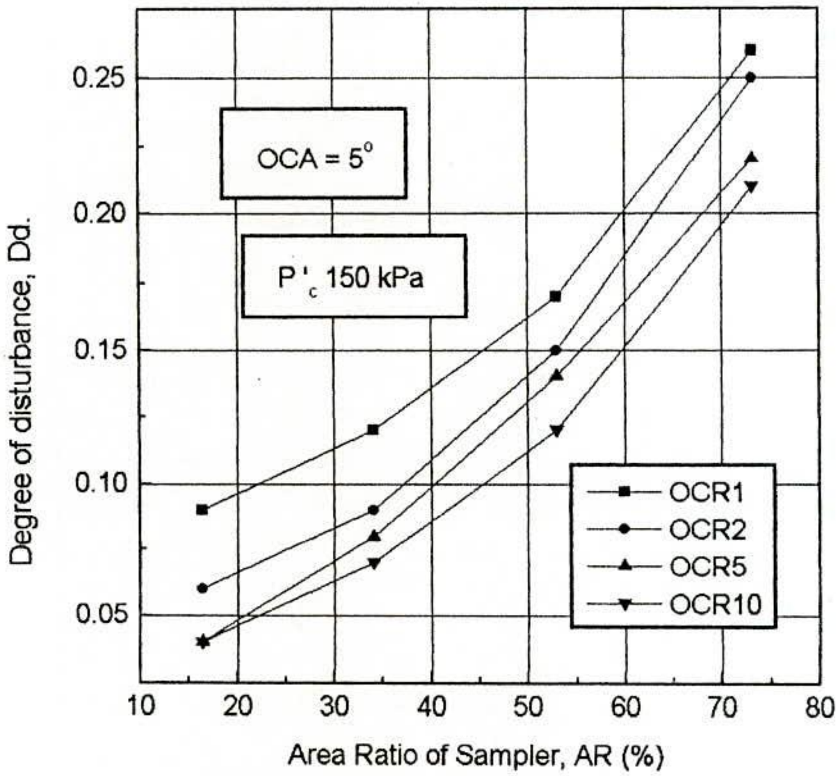


Fig. 5.38. Variation of degree of disturbance with area ratio (%) of sampler for samples of Dhaka clay for different OCR.

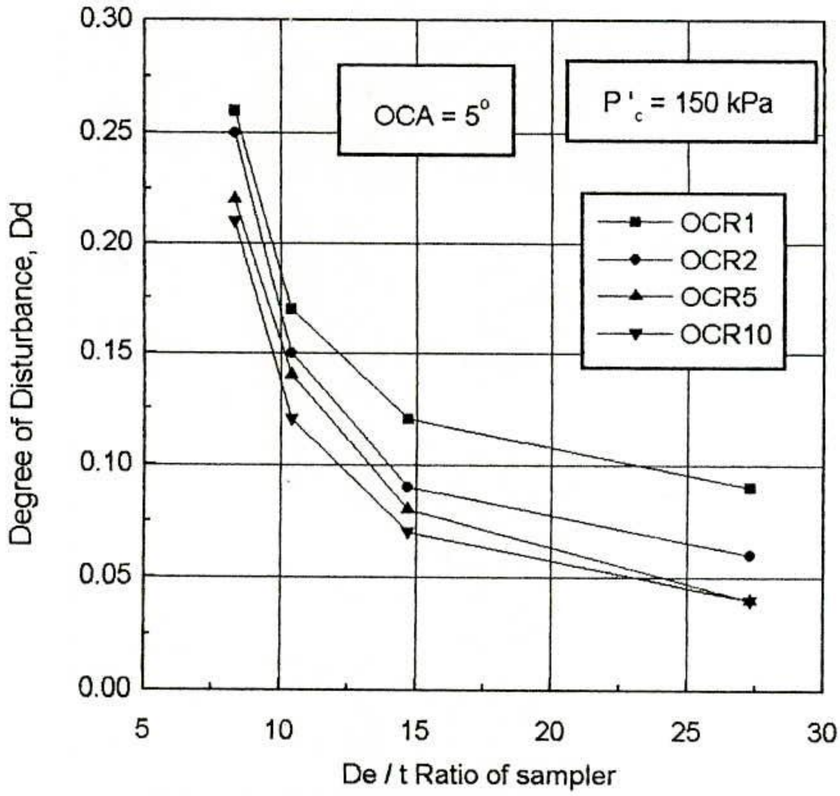


Fig. 5.39. Variation of degree of disturbance with De/t ratio of sampler for samples of Dhaka clay for different OCR.

The typical variation of D_d with OCR for "tube" samples of two tube samplers (T1 and T4) is shown in Fig. 5.41. It is evident from Fig.5.41 that the degree of disturbance reduces with increasing OCR for Dhaka clay. Siddique et al. (1999) also reported that ideal tube sampling caused less disturbance in overconsolidated reconstituted London clay (OCR = 4), compared with normally consolidated reconstituted London clay.

5.7 CORRECTION OF UNCONSOLIDATED UNDRAINED STRENGTH OF DHAKA CLAY

Ladd and Lambe (1963) suggests that the strength from unconsolidated undrained (UU) tests can be considered as test results on overconsolidated specimens with a maximum past pressure equal to σ'_{ps}, the value of effective stress existing before gross sample disturbance occurred. Thus the corrected value of s_u from UU tests, which will correspond to the strength of a specimen after perfect sampling, can be estimated by treating the ratio of σ'_{ps} to σ'_i as an overconsolidation ratio, where $\sigma'_i = \sigma'_r$ is the initial or residual effective pressure. Based on the procedure suggested by Ladd and Lambe (1963), the method of correcting undrained shear strength for sample disturbance involves the following three steps:

1. It is related the undrained shear strength to overconsolidation ratio using isotropically consolidated undrained (CIU) tests on specimens with σ'_{ps} much greater than σ'_i to reduce the effects of disturbance,
2. The equivalent overconsolidation ratio is found for the UU test being corrected by measuring σ'_i and calculating σ'_{ps} and
3. The shear strength correction value is obtained for the particular overconsolidation ratio obtained from strength ratio (s_u at σ'_c to s_u at σ'_{cm}) versus OCR curve.

Fig.5.42 presents the plot of strength ratio (s_u at σ'_i to s_u at σ'_{ps}) versus overconsolidation ratio (σ'_{ps} / σ'_i) for CIU tests on Dhaka clay. As can be seen, the strength ratio decreases significantly with an increase in OCR. Considering the ratio of σ'_{ps} to σ'_i equivalent to OCR, the loss in shear strength from excessive sample disturbance which reduces the effective stress from σ'_{ps} to σ'_i can be estimated from Fig.5.42. From the isotropic and residual effective

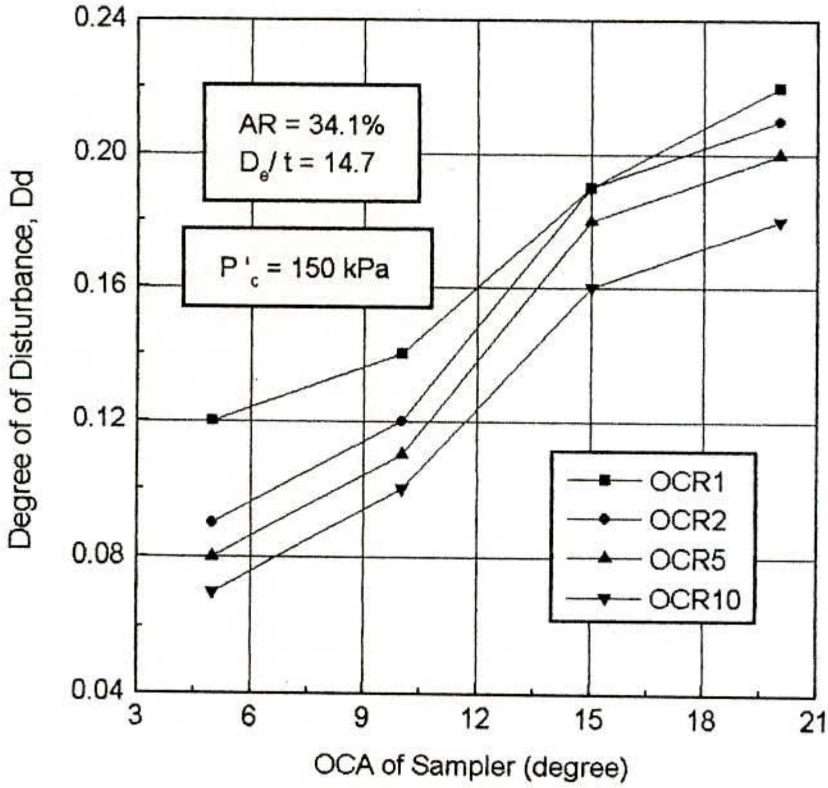


Fig. 5.40. Variation of disturbance with OCA of sampler (degree) for samples of Dhaka clay for different OCR.

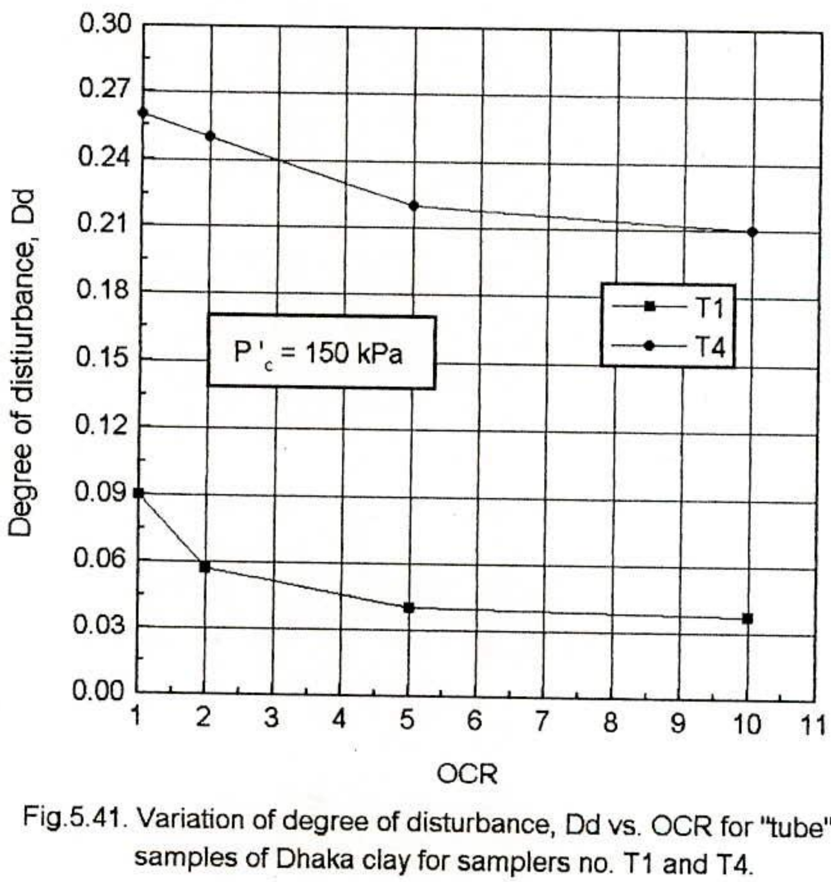


Fig.5.41. Variation of degree of disturbance, Dd vs. OCR for "tube" samples of Dhaka clay for samplers no. T1 and T4.

stress data, a typical value of σ'_{ps} / σ'_i might be 2 to 5, the equivalent OCR, using the data from Fig.5.42, it can be seen that measured values of UU strength would be 15 to 29 percent too low depending on the nature of Dhaka clay.

As an example, the application of the strength correction curve can be explained that for the "tube" samples obtained with a sampler T4. For values of residual or initial effective stress, $\sigma_i' = 65.4$ kPa and maximum or isotropic effective stress $\sigma_{ps}' = 88.7$ kPa, OCR (σ'_{ps} / σ'_i) of the sample is 88.7 / 65.4 = 1.36. It is found from the curve in Fig. 5.42 that corresponding the ratio of $\sigma'_{ps} / \sigma'_i = 1.36$, the ratio of s_u at σ'_i to s_u at σ'_{ps} is equal to 0.90. The measured undrained shear strength, s_u of the sample is 33.2 kPa, and the corrected strength should be 33.2 / 0.90 = 36.9 kPa.

5.8 ASSESSMENT OF INFLUENCE OF PERFECT SAMPLING DISTURBANCE IN NORMALLY CONSOLIDATED AND OVERCONSOLIDATED DHAKA CLAY

The undrained shear behaviour of "perfect" samples of normally consolidated and overconsolidated Dhaka clay has been studied. "Perfect" sample has been modeled on Dhaka clay for OCR values of 1, 2, 5, and 10, in the laboratory by undrained release of the total stresses and sheared in compression under undrained condition up to failure. The values of, A_u (Skempton's pore pressure parameter for the undrained release of shear stress) and the isotropic effective stress, σ_{ps}' of the "perfect" sample have been determined using Equation nos. 2.6 and 2.5, respectively. The values of isotropic effective stress, σ'_{ps} for "perfect" samples are 88.7 kPa, 40.4 kPa, 15.1 kPa and 7.2 kPa, and the values of A_u are 0.182, 0.077, 0.0053 and -0.0464 of Dhaka clay for OCR values of 1, 2, 5, and 10, respectively. The values of, $\sigma'_{ps} / \sigma'_{vc}$ for "perfect" samples are 0.59, 0.54, 0.503 and 0.48 for OCR values of 1, 2, 5 and 10, respectively. It has been found that the values of A_u and $\sigma'_{ps} / \sigma'_{vc}$ of "perfect" samples reduce with increase in OCR for the samples of Dhaka clay.

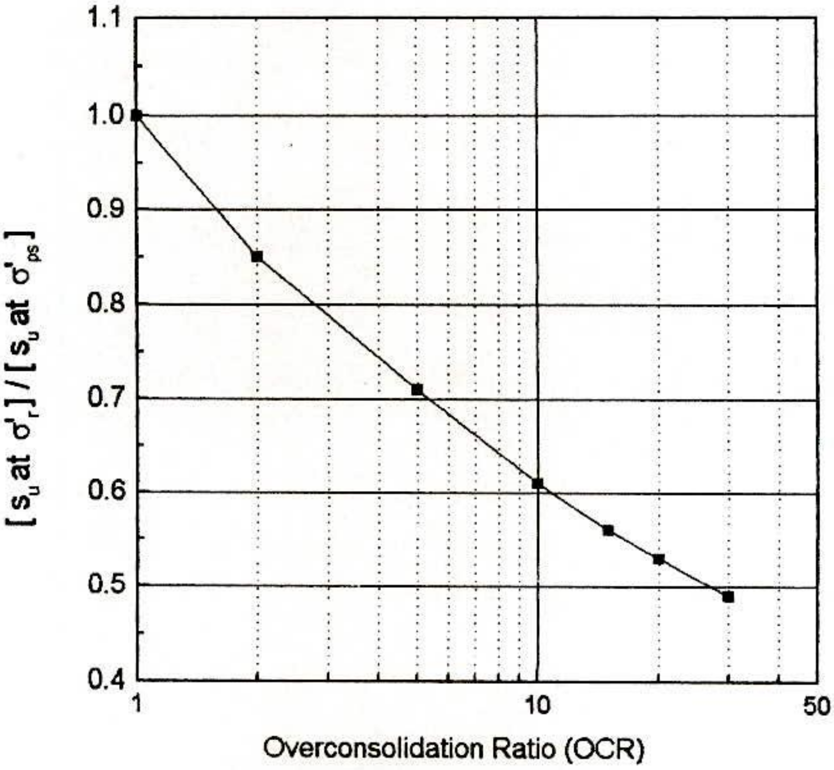


Fig.5.42 Undrained Shear Strength correction curve of Dhaka clay.

5.8.1 CHANGES IN EFFECTIVE STRESS PATHS

A comparison of the effective stress paths, in s′-t′ [$s' = (\sigma_a' + \sigma_r')/2$, $t' = (\sigma_a' - \sigma_r')/2$] space for the "in situ" and "perfect" samples of Dhaka clay for OCR values of 1, 2, 5, and 10 is presented in Fig. 5.43. It can be seen from Fig. 5.43 that for the normally consolidated "in situ" sample, initially s′ decreases with the increase in t′ and then it increases with further increase in t′, as failure approaches. For the normally consolidated and overconsolidated "perfect" sample, however, s′ increases with the increase in t′ throughout whole stage of undrained shearing. The nature of the effective stress path of the normally consolidated "perfect" sample has markedly different from that of the respective "in situ" sample. Significant difference in stress path between normally consolidated "in situ" and "perfect" samples has also been reported for the regional clays of Bangladesh (Siddique and Farooq,1996; Bashar et al.1997a; Siddique and Sarker,1998). It is found from Fig. 5.43 that the nature of the effective stress paths of the overconsolidated "in situ" and "perfect" samples were similar.

5.8.2 CHANGE IN STRENGTH, STRAIN AND STIFFNESS PROPERTIES

Fig. 5.44 shows the deviator stress versus axial strain plots for the "in situ" and "perfect" samples of normally consolidated and overconsolidated Dhaka clay. From the stress-strain data, the values of s_u, E_i, E_{50} and ε_p have been determined for both the "in situ" and "perfect" samples. A comparison of the undrained soil parameters of the "in situ" and "perfect" samples are presented in Table 5.14. The test results are not corrected with respect to water content. It can be seen from Table 5.14 that because of the relief of total stress, the values of s_u decreased by 4.4%, 5.9%, 7.9%, and 8.2%, while, the values of ε_p increased by 7.2%, 8.9%, 19.7% and 20.9% for OCR values of 1, 2, 5 and 10, respectively. Table 5.14 also shows that because of disturbance due to stress release, compared with the "in situ" sample, the values of E_i increased by 14%, 9.2%, 8.5%, and 7.6%, and also the values of E_{50}, increased by 19%, 10.9%, 10.7%, and 9.9%, of the "perfect" samples of Dhaka clay (PI = 26) for OCR values of 1, 2, 5, and 10, respectively. Reduction in s_u and increase in ε_p, E_i and E_{50} due to perfect sampling disturbance has also been

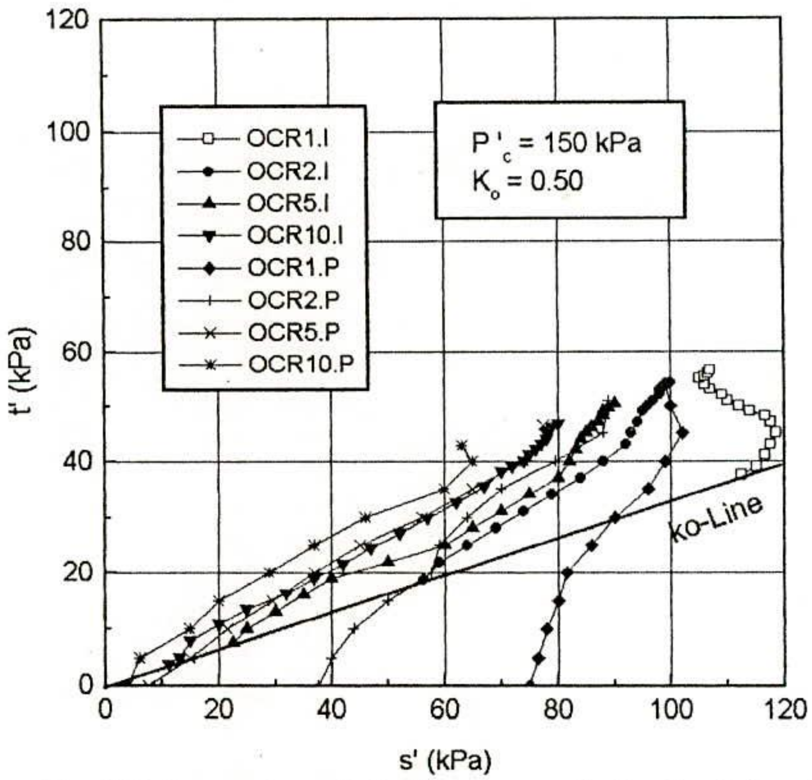


Fig. 5.43. Comparison of effective stress paths for "in situ" and "perfect" samples of Normally consolidated and Over-consolidated Dhaka Clay.

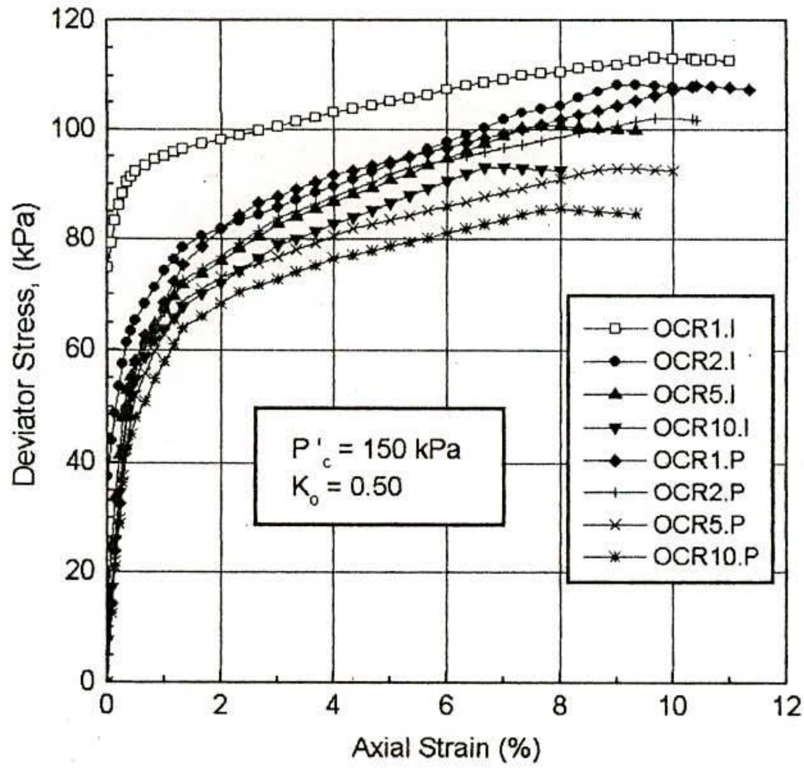


Fig.5.44 Deviator Stress vs. Axial strain (%) plots for "in situ" and "perfect" samples of Normally consolidated and Overconsolidated Dhaka Clay.

reported for normally consolidated reconstituted samples of Dhaka clay and coastal soils of Bangladesh (Siddique and Sarker, 1998; Siddique and Farooq,1996; Bashar et, al. 1997a).

Due to relief of total stress for "perfect" samples, the reduction in s_u and increase in ε_p and E_i of normally consolidated for soft Dhaka clay (Siddique and Sarker,1998) are greater than those of the firm Dhaka clay of the present investigation.

Kirkpatrick and Khan (1984) and Kirpatrick et al. (1986) also reported reduction in s_u and increase in ε_p for normally consolidated and overconsolidated samples of kaolin and Illite. Kirkpatrick and Khan (1984) and Kirpatrick et al. (1986), however, found considerable reduction in secant stiffness at peak deviator stress in both normally consolidated and overconsolidated samples of Kaolin and Illite. These findings contrast with those obtained in the present investigation.

Fig. 5.45 represents the plot of reduction in s_u versus OCR for "perfect" samples of Dhaka clay. It is evident from Fig. 5.45 that the reduction in undrained shear strength increases with increase in OCR. This finding contrast with that reported by Kirpatrick et al. (1986). Kirpatrick et al. (1986) found an increase in s_u with the increase in OCR for perfect samples of Illite.

Due relief of total stress, the increase in E_i and E_{50} for "perfect" samples of normally consolidated and overconsolidated Dhaka clay, however, reduced with increase in OCR. It has been found that the increase in the value of ε_p increases with increasing OCR of Dhaka clay.

5.8.3 CHANGES IN PORE PRESSURE RESPONSE

Fig. 5.46 shows a comparison of the change in pore pressure with axial strain during shearing between the normally consolidated and overconsolidated "in situ" and "perfect" samples of Dhaka clay. It can be seen from Fig. 5.46 that, compared with the "in situ" sample the change in pore pressure for the "perfect" samples are considerably less. From Fig. 5.46, it appears that for the "perfect" samples at low strains the pore pressure increases rapidly with the increase in deviator stress. The pore pressures, however, typically start to decrease before the peak deviator stress has reached resulting in considerably lower values than those for the "in situ" sample.

The values of A_p for the "perfect" and "in situ" samples are also in Table 5.14. It can be showed from Table 5.14 that the values of A_p of the "perfect" samples are very small as compared to the A_p of "in situ" samples for different overconsolidation ratios because of disturbance due to stress relief. It can also be seen from Table 5.14 that due to the relief of total stress, the values of pore pressure parameter at peak deviator stress (A_p), reduced by 90%, 79%, 75% and 72% for OCR values of 1, 2, 5 and 10, respectively. The reduction in value of A_p reduces with increasing OCR for "perfect" samples of Dhaka clay. Siddique and Sarker (1998) and Siddique and Farooq (1996) also reported that the significant reduction in A_p because of disturbance due to perfect sampling in normally consolidated Dhaka clay and coastal soils, respectively.

Table 5.14 Undrained Shear Characteristics of "Perfect" and "In Situ" Samples

Sample Designation	s_u (kN/m^2)	ε_p (%)	E_i (kN/m^2)	E_{50} (kN/m^2)	A_p
OCR_1-P	54.1	10.4	32490	27300	0.043
OCR_1-I	56.6	9.7	28500	22950	0.42
OCR_2-P	51.0	9.8	28970	24120	0.039
OCR_2-I	54.2	9.0	26530	21750	0.19
OCR_5-P	46.4	9.1	26450	22650	0.035
OCR_5-I	50.4	7.6	24380	20450	0.14
OCR_{10}-P	42.8	8.1	23920	20830	0.036
OCR_{10}-I	46.6	6.7	22230	18950	0.13

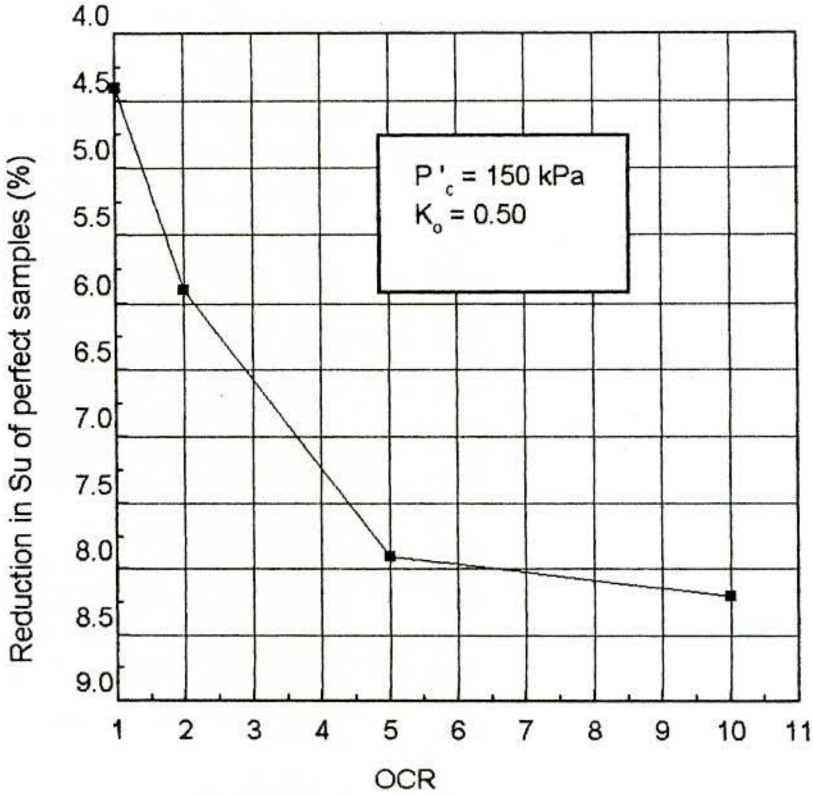


Fig. 5.45. Variation of % Reduction in shear strength with OCR for perfect samples.

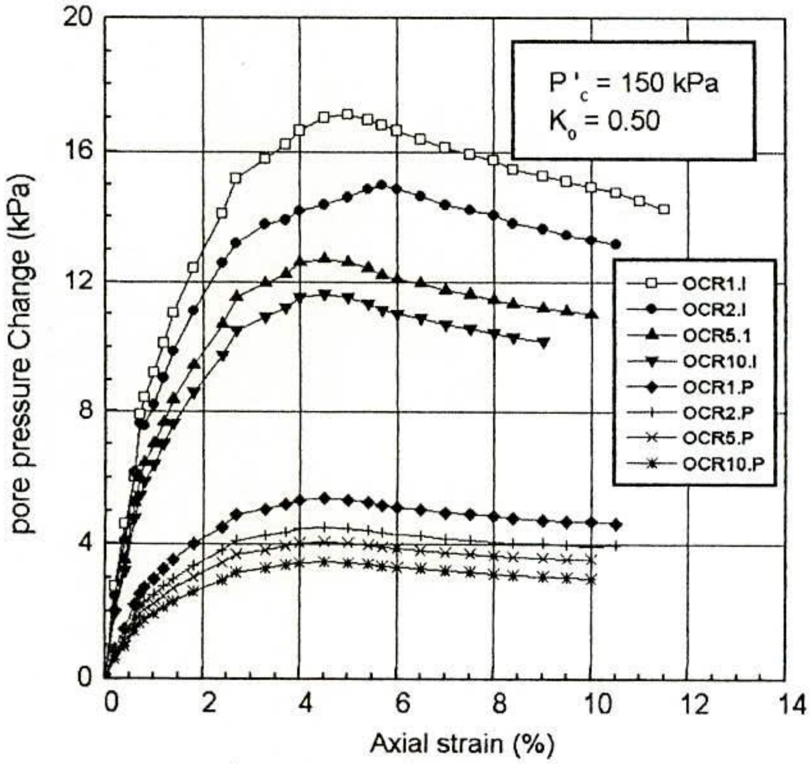


Fig.5.46 Pore pressure change versus Axial strain(%) plots for "in situ" and "perfect" samples of Normally consolidated and Overconsolidated Dhaka Caly.

5.10 ASSESSMENT OF INFLUENCE OF "RECONSOLIDATION" ON RECONSTITUTED OVERCONSOLIDATED DHAKA CLAY

The undrained stress-strain-strength, stiffness and pore pressure response due to reconsolidation has been investigated for both "tube" and "perfect" samples. Isotropic and anisotropic reconsolidation procedures were adopted in order to assess the suitability of different reconsolidation procedure to minimize the sampling disturbance effects in overconsolidated Dhaka clay. Reconsolidation was carried out on both the "tube" and "perfect" samples of Dhaka clay for OCR values of 2 and 10. The following two reconsolidation methods were used for the "tube" and "perfect" samples:

(i) Isotropic Reconsolidation: Samples were reconsolidated using hydrostatic consolidation stress equal to initial vertical effective stress, σ'_{vc} of the "in situ" sample. A back pressure of 270 kN/m^2 has been used during isotropic consolidation of the sample.

(ii) Anisotropic reconsolidation using Bjerrum (1973) procedure: Samples were reconsolidated under K_0-consolidation to vertical effective stresses equal to 1.0 times the effective initial vertical stress (σ'_{vc}) of the "in situ" sample. A back pressure of 270 kN/m^2 has been used during K_0-consolidation of the samples.

(iii) Anisotropic reconsolidation using SHANSEP (Ladd and Foott, 1974) procedure: samples were reconsolidated anisotropically using SHANSEP procedure to vertical effective stresses equal to 1.5 and 2.5 times the effective initial vertical stress (σ'_{vc}) of the "in situ" sample. A back pressure of 270 kN/m^2 has been used during K_0-consolidation of the samples.

5.10.1 RECONSOLIDATED "TUBE" SAMPLES

Reconsolidation was carried out on "tube" samples which were retrieved using the sampler of area ratio = 34.1% (t = 3.0 mm), D_e/t = 14.7 and OCA = 5°. The undrained soil parameters of the reconsolidated "tube" samples have been determined from stress-strain and pore pressure data. The soil parameters of the reconsolidated "tube" samples are presented in Tables 5.15 and 5.16 for Dhaka clay for OCR values of 2 and 10, respectively. In Tables 5.15 and 5.16, the respective soil parameters of "in situ" sample are also shown for comparison. The test results are not corrected with respect to water content.

It can be seen from Tables 5.15 and 5.16 that isotropic reconsolidation, using an effective consolidation pressure equal to σ'_{vc} (which are 75 kN/m^2 and 15 kN/m^2 for samples of Dhaka clay for OCR values of 2 and 10 respectively) of the "in situ" sample, has the effect of significant overestimation of "in situ" undrained shear strength (s_u), axial strain at peak deviator stress (ε_p), initial tangent modulus (E_i), secant stiffness at half of the peak deviator stress (E_{50}) and pore pressure parameter at peak deviator stress (A_p) for both OCR-values. It can be seen from Tables 5.15 that s_u, ε_p, E_i, E_{50} and A_p increased by 16.7%, 33.3%, 36.7%, 15.3% and 21.1%, respectively due to isotropic reconsolidation of "tube" samples for OCR values of 2. It can also be seen from Tables 5.16 that s_u, ε_p, E_i, E_{50} and A_p increased by 11.6%, 49.2%, 11.6%, 19.7% and 30.7%, respectively due to isotropic reconsolidation of "tube" samples for OCR values of 10. Siddique et al. (2000) also reported that s_u, ε_p and E_i increased while A_p decreased due to isotropic reconsolidation in two normally consolidated soft samples of coastal soils.

It can also be seen from Tables 5.15 and 5.16 that undrained strength ratio (s_u/σ_{vc}') and stiffness ratios (E_i/σ_{vc}' and E_{50}/σ_{vc}') reduce while the values of ε_p and A_p increase due to reconsolidation of Bjerrum procedure and SHANSEP procedures for "tube" samples of both OCR values. For OCR of 2, the following changes in undrained soil parameters between "in situ" samples and "tube" samples reconsolidated anisotropically under K_0-consolidation were found:

(i) s_u/σ_{vc}' reduced by 4.4%, 18.5% and 21.2% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

(ii) E_i/σ_{vc}' reduced by 19.0%, 36.1% and 49.0% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

(iii) E_{50}/σ_{vc}' reduced by 25.1%, 39.1% and 48.3% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

(iv) ε_p increased by 3.3%, 25.6% and 44.4% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

(v) A_p increased by 10.5%, 73.6% and 89.5% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

For OCR of 10, the following changes in undrained soil parameters between "in situ" samples and "tube" samples reconsolidated anisotropically under K_0-consolidation were found:

(i) s_u/σ_{vc}' reduced by 4.8%, 24.5% and 30.0% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

(ii) E_i/σ_{vc}' reduced by 29.1%, 39.0% and 52.6% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

(iii) E_{50}/σ_{vc}' reduced by 32.4%, 42.3% and 51.6% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

(iv) ε_p increased by 19.4%, 29.8% and 58.2% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

(v) A_p increased by 15.4%, 131% and 146% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

The above results indicate that compared with SHANSEP reconsolidation procedures for both OCR-values, the soil parameters of "tube" samples reconsolidated using Bjerrum procedure (CK_0U-1.0 σ'_{vc}) agrees more closely with those of the respective "in situ" samples than those of the samples reconsolidated using SHANSEP procedures. Siddique et al. (2000) reported that reconsolidation of "tube" samples using SHANSEP-1.5 procedue produced better agreement with the characteristics of the respective "in situ" samples for reconstituted normally consolidated two coastal soils. Sarker (1994) reported that K_o-reconsolidation of "tube" samples using the SHANSEP procedures could not restore "in situ" behaviour. Siddique et al. (2000) and Sarker (1994), however, did not adopt the reconsolidation of "tube" samples using Bjerrum procedure in their investigations.

The normalized deviator stress versus axial strain plots of the reconsolidated "tube" samples of Dhaka clay for OCR values of 2 and 10 are presented in Figs. 5.47 and 5.48, respectively. In Figs. 5.47 and 5.48, the corresponding plots for the respective "in situ" sample are also shown for comparison with the reconsolidated "tube" samples. It is observed from Figs. 5.47 and 5.48 that the plot of the sample reconsolidated using Bjerrum procedure agrees most favourably with the "in situ" sample.

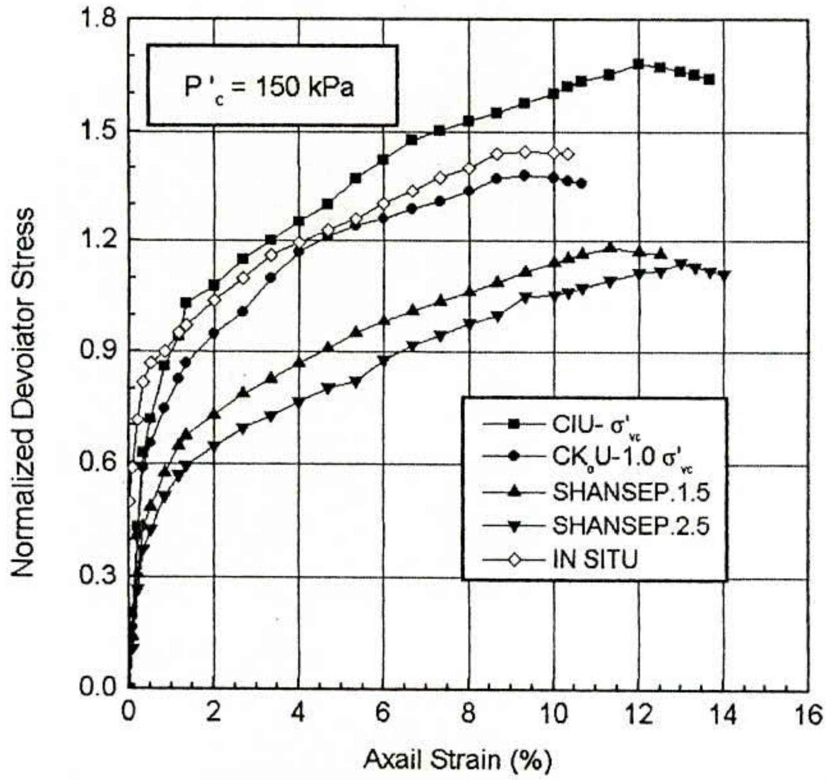


Fig.5.47 Normalized Deviator Stress versus Axail Strain (%) plots for "In situ" and Reconsolidated "Tube" samples of Dhaka Clay for OCR = 2 sampling by T2.

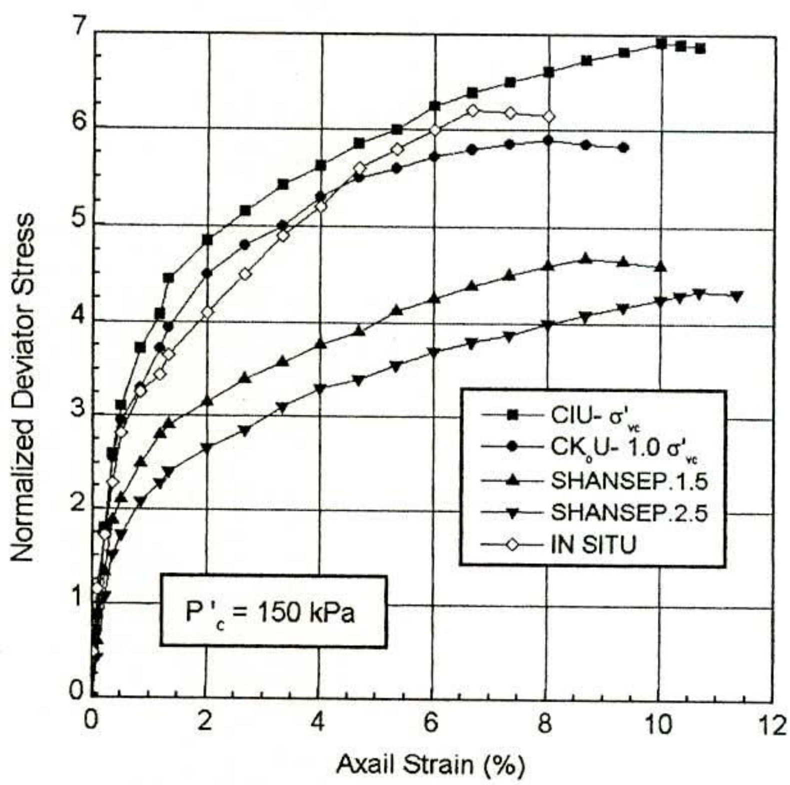


Fig.5.48 Normalized Deviator Stress versus Axail Strain (%) plots for "In situ" and Reconsolidated "Tube" samples of Dhaka Clay for OCR = 10 sampling by T2.

The variations of pore pressure parameter with axial strain of the reconsolidated "tube" samples of Dhaka clay for OCR values of 2 and 10 are presented in Figs. 5.49 and 5.50, respectively. In Figs. 5.49 and 5.50, the corresponding plots for the "in situ" sample are also shown. Figs. 5.49 and 5.50 also show the plot of sample reconsolidated using Bjerrum procedure produces better agreement with the "in situ" sample than those of samples reconsolidated using Isotropic and SHANSEP reconsolidation procedures.

Table 5.15 Comparison of Undrained Shear characteristics of "In Situ" and Reconsolidated "Tube" Samples of Dhaka Clay at OCR =2.

Sample Designation	Test Type	s_u / σ'_{vc}	ε_p (%)	E_i / σ'_{vc}	E_{50} / σ'_{vc}	A_p
OCR_2-T2	CIU-1.0 σ'_{vc}	0.84	12.0	483.4	334.5	0.23
OCR_2-T2	CK_OU-1.0 σ'_{vc}	0.69	9.3	286.5	217.2	0.21
OCR_2-T2	SHANSEP-1.5	0.59	11.3	226.1	176.6	0.33
OCR_2-T2	SHANSEP-2.5	0.57	13.0	180.5	149.7	0.36
OCR_2-I	"In Situ"	0.72	9.0	353.8	290.0	0.19

Table 5.16 Comparison of Undrained Shear characteristics of "In Situ" and Reconsolidated "Tube" Samples of Dhaka Clay at OCR =10.

Sample Designation	Test Type	s_u / σ'_{vc}	ε_p (%)	E_i / σ'_{vc}	E_{50} / σ'_{vc}	A_p
OCR_{10}-T2	CIU-1.0 σ'_{vc}	3.46	10.0	1653.3	1511.9	0.17
OCR_{10}-T2	CK_OU-1.0 σ'_{vc}	2.95	8.0	1050.6	853.0	0.15
OCR_{10}-T2	SHANSEP-1.5	2.34	8.7	904.0	728.8	0.30
OCR_{10}-T2	SHANSEP-2.5	2.17	10.6	701.8	611.8	0.32
OCR_{10}-I	"In Situ"	3.10	6.7	1482.0	1263.0	0.13

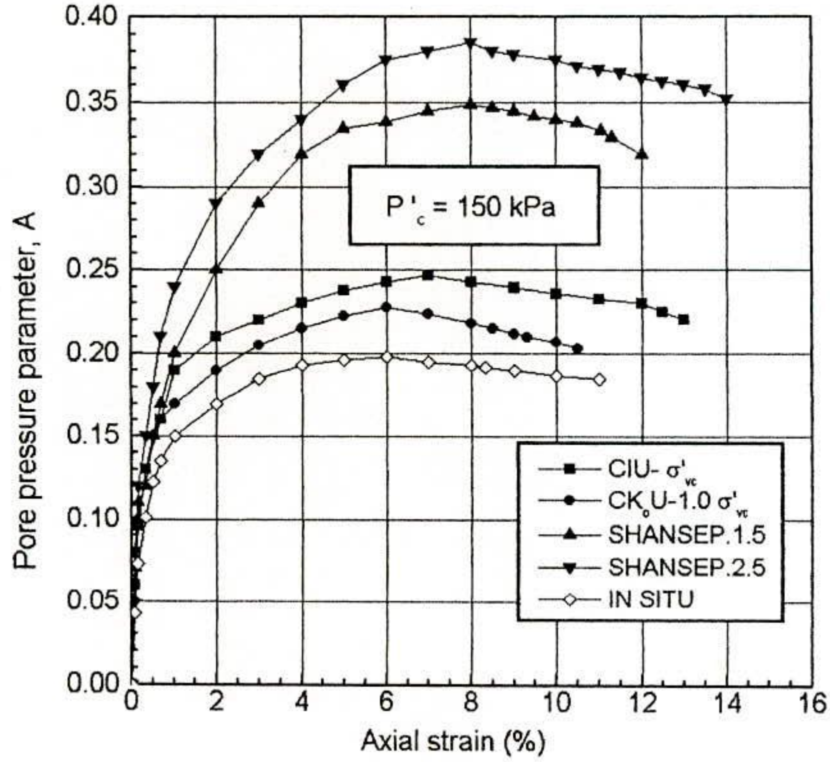


Fig.5.49 Pore pressure parameter vs. axial strain plots for "in situ" and reconsolidated "tube" samples of OCR=2.

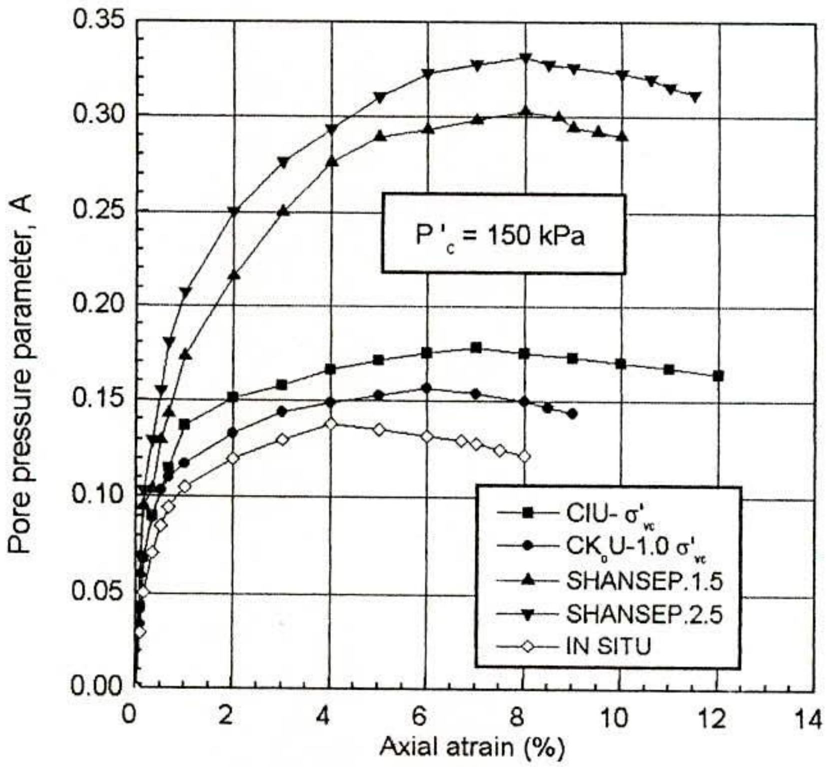


Fig.5.50 Pore pressure parameter, vs. axial strain plost for "in situ" and reconsolidated "tube" samples of OCR = 10.

5.10.2 RECONSOLIDATED "PERFECT" SAMPLE

Undrained shear strength (s_u), stiffnesses (E_i and E_{50}) and pore pressure parameter at peak deviator stress (A_p) have been determined from the stress-strain and pore pressure data of reconsolidated "perfect" samples. A comparison of undrained soil parameters of reconsolidated "perfect" samples are presented in Tables 5.17 and 5.18 for Dhaka clay for OCR values of 2 and 10 respectively. In Table 5.17 and 5.18, the respective soil parameters of "in situ" sample are also shown for comparison. The test results are not corrected with respect to water content.

It can be seen from Tables 5.17 and 5.18 that isotropic reconsolidation has the effect of marked overestimation of "in situ" undrained shear strength (s_u), axial strain at peak deviator stress (ε_p) stiffnesses (E_i and E_{50}) and pore pressure parameter at peak deviator stress (A_p) for both OCR values. It can be seen from Tables 5.17 that s_u, ε_p, E_i, E_{50} and A_p increased by 20.8%, 25.5%, 60.3%, 37.9% and 36.8% respectively due to isotropic reconsolidation of "perfect" samples for OCR values of 2. It can also be seen from Tables 5.18 that s_u, ε_p, E_i, E_{50} and A_p increased by 14.8%, 49.2%, 49.5%, 23.3% and 46.1% respectively due to isotropic reconsolidation of "perfect" samples for OCR values of 10. Siddique et al. (2000) also reported that s_u, E_i, ε_p and A_p increased due to isotropic reconsolidation of "perfect" samples for three normally consolidated coastal soils.

Tables 5.17 and 5.18 show the values of s_u/σ_{vc}', E_i/σ_{vc}' and E_{50}/σ_{vc}' reduce while the value of ε_p and A_p increases due to reconsolidation of Bjerrum procedure and SHANSEP procedures for "perfect" samples of both OCR values. For OCR of 2, the following changes in undrained soil parameters between "in situ" samples and "perfect" samples reconsolidated anisotropically under K_0-consolidation were found:

(i) s_u/σ_{vc}' reduced by 2.7%, 12.5% and 13.8% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

(ii) E_i/σ_{vc}' reduced by 5.9%, 23.9% and 39.1% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

(iii) E_{50}/σ_{vc}' reduced by 5.4%, 18.4% and 34.7% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

(iv) ε_p increased by 3.3%, 5.6% and 18.9% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

(v) A_p increased by 15.7%, 94.7% and 115.7% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

For OCR of 10, the following changes in undrained soil parameters between "in situ" samples and "perfect" samples reconsolidated anisotropically under K_0-consolidation were found:

(i) s_u/σ_{vc}' reduced by 2.6%, 18.4% and 23.2% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

(ii) E_i/σ_{vc}' reduced by 12.4%, 30.4% and 46.6% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

(iii) E_{50}/σ_{vc}' reduced by 13.3%, 25.2% and 42.2% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

(iv) ε_p increased by 8.9%, 26.8% and 38.8% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

(v) A_p increased by 30.1%, 138% and 161% in samples reconsolidated using Bjerrum, SHANSEP-1.5 and SHANSEP-2.5 procedures respectively.

It appears from the above findings that for both OCR-values, compared with SHANSEP reconsolidation procedures, the soil parameters of "perfect" samples reconsolidated using Bjerrum procedure (CK_OU-1.0 σ'_{vc}) agrees more closely with those of the respective "in situ" samples than those of the samples reconsolidated using SHANSEP procedures. Siddique et al. (1997) also reported that reconsolidation using Bjerrum procedure produced the best estimate of the "in situ" samples for three coastal soils. Siddique and Sarker (1998) reported that reconsolidation of "perfect" specimens using SHANSEP procedures could not restore the characteristics of the "in situ" specimen for normally consolidated Dhaka clay. Siddique and Farooq (1996) found that K_o-reconslidation of "perfect" sample to in SHANSEP-1.5σ'_{vc} produced the best agreement for two coastal soils. Siddique and Sarker (1998) and Siddique and Farooq (1996), however did not adopt the reconsolidation of "perfect" samples using Bjerrum procedure.

Table 5.17 Comparison of Undrained Shear characteristics of "In Situ" and Reconsolidated "Perfect" Samples of Dhaka Clay at OCR =2.

Sample Designation	Test Type	s_u / σ'_{vc}	ε_p (%)	E_i / σ'_{vc}	E_{50} / σ'_{vc}	A_p
OCR_2-P	CIU-1.0 σ'_{vc}	0.87	11.3	567.2	400.5	0.26
OCR_2-P	CK_OU-1.0 σ'_{vc}	0.70	9.3	332.6	274.2	0.22
OCR_2-P	SHANSEP-1.5	0.63	9.5	269.2	236.7	0.37
OCR_2-P	SHANSEP-2.5	0.62	10.7	215.3	189.4	0.41
OCR_2-I	"In Situ"	0.72	9.0	353.8	290.0	0.19

Table 5.18 Comparison of Undrained Shear characteristics of "In Situ" and Reconsolidated "Perfect" Samples of Dhaka Clay at OCR =10.

Sample Designation	Test Type	s_u / σ'_{vc}	ε_p (%)	E_i / σ'_{vc}	E_{50} / σ'_{vc}	A_p
OCR_{10}-P	CIU-1.0 σ'_{vc}	3.56	10.0	2216.0	1557.6	0.19
OCR_{10}-P	CK_OU-1.0 σ'_{vc}	3.02	7.3	1298.6	1095.0	0.17
OCR_{10}-P	SHANSEP-1.5	2.53	8.5	1032.2	944.0	0.31
OCR_{10}-P	SHANSEP-2.5	2.38	9.3	790.8	729.7	0.34
OCR_{10}-I	"In Situ"	3.10	6.7	1482.0	1263.0	0.13

The normalized deviator stress versus axial strain plots for the reconsolidated "perfect" sample of Dhaka clay for OCR values 2 and 10 are presented in Figs. 5.51 and 5.52 respectively. Figs. 5.51 and 5.52 also show the corresponding plots for the "in situ" sample for comparison with the reconsolidated samples. It can be seen from Figs. 5.51 and 5.52 that the

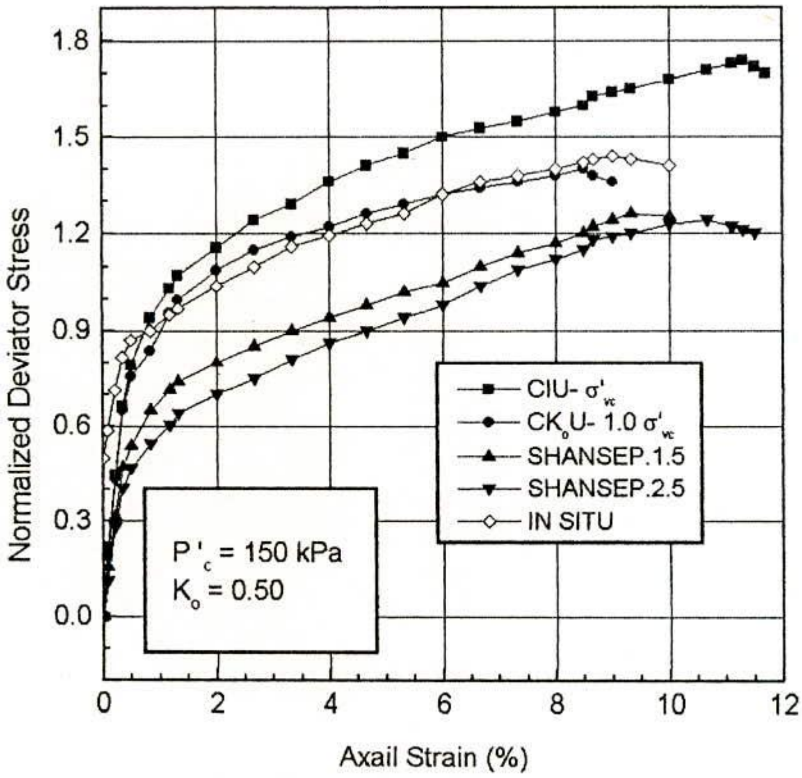


Fig.5.51 Normalized Deviator Stress vs. Axail Strain (%) plots for "In situ" and Reconsolidated "Perfect" samples of Dhaka Clay for OCR = 2.

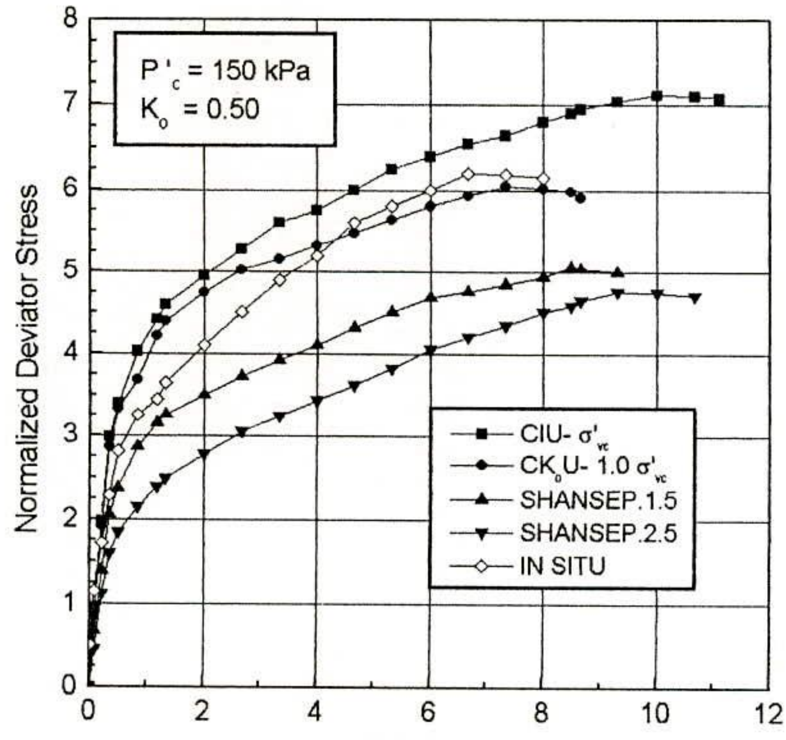


Fig.5.52 Normalized Deviator Stress vs. Axail Strain (%) plots for "In situ" and Reconsolidated "Perfect" samples of Dhaka Clay for OCR = 10

plot of the sample reconsolidated using Bjerrum procedure agrees most favourably with the "in situ" sample.

The variations of pore pressure parameter with axial strain for the reconsolidated "perfect" sample of Dhaka clay for OCR values 2 and 10 are presented in Figs. 5.53 and 5.54 respectively. Figs. 5.53 and 5.54 also show the plot of the sample reconsolidated using Bjerrum reconsolidation procedure produces better agreement with the "in situ" sample than those of the samples reconsolidated using Isotropic and SHANSEP reconsolidation procedures.

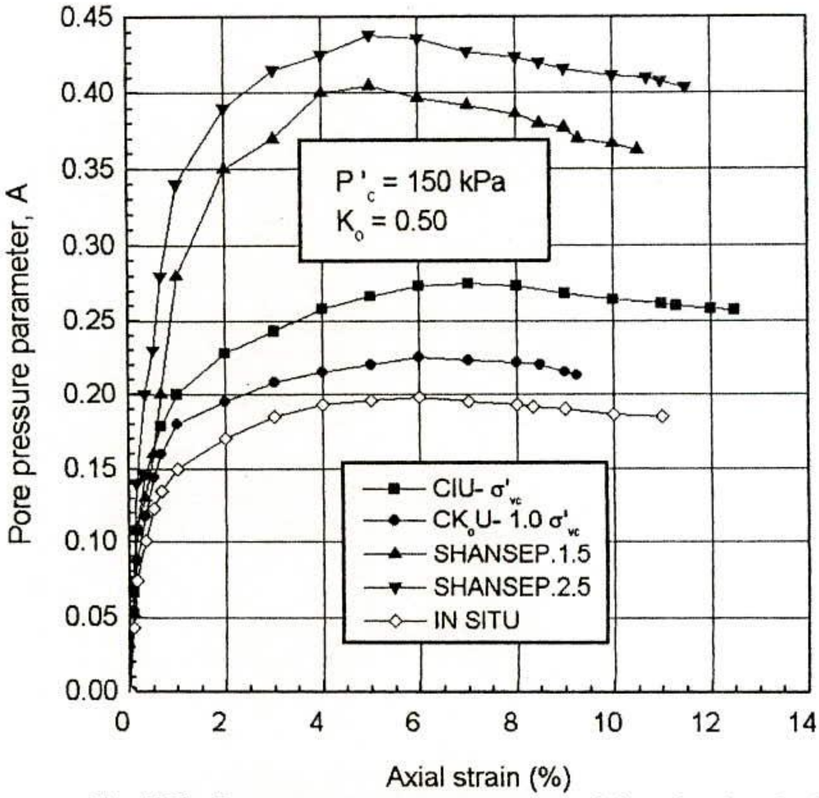


Fig. 5.53 Pore pressure parameter vs. axial strain plots for "n situ" and reconsolidated "perfect" samples of OCR = 2

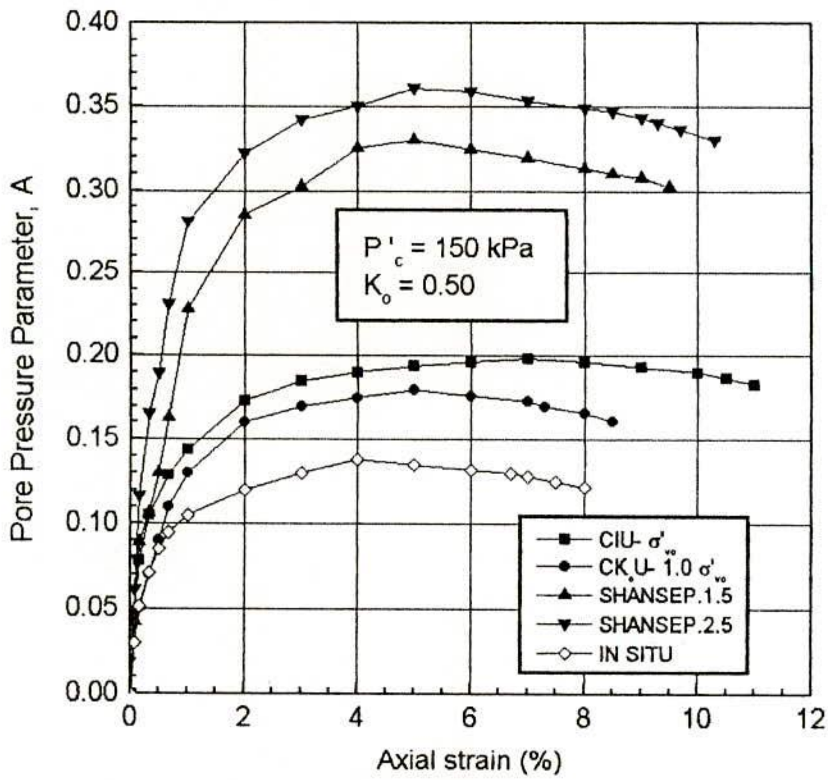


Fig.5.54 Pore pressure parameter vs. axial strain plots for "in situ" and reconsolidated "perfect" sample of OCR = 10.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

6.1 CONCLUSIONS

In this research, the effects of tube and perfect sampling disturbance on undrained shear characteristics have been investigated for reconstituted normally consolidated and overconsolidated (OCR values of 2, 5 and 10) Dhaka clay. The influence of the sampler characteristics, namely, area ratio and outside cutting edge angle on the measured soil parameters has also been examined. Attempt influence of stress history on tube and perfect sampling disturbance effects in samples of Dhaka clay has been made to examine. The suitability of different reconsolidation of "tube" and "perfect" samples using different reconsolidation procedures has been assessed in order to restore "in situ" behaviour. The main findings and conclusions have been separated into four sections relating to the following areas:

(1) The influence of tube sampling disturbance on the undrained shear parameters of samples for reconstituted normally consolidated and overconsolidated Dhaka clay.

(2) The effect of perfect sampling disturbance on undrained shear parameters of samples for reconstituted normally consolidated and overconsolidated Dhaka clay.

(3) The influence of stress history on tube and perfect sampling disturbance effects in samples of Dhaka clay.

(4) Reconsolidation effect in "tube" and "perfect" samples of reconstituted overconsolidated Dhaka clay for OCR values of 2 and 10.

6.1.1 INVESTIGATION OF THE INFLUENCE OF TUBE SAMPLING DISTURBANCE IN DHAKA CLAY

Effects of tube sampling disturbance on undrained stress-strain-strength, stiffness and pore pressure characteristics have been investigated for reconstituted normally consolidated and overconsolidated samples of Dhaka clay. The major findings and conclusions of the present investigation are summarized below:

1. Disturbance due to tube sampling led to reduction in the values of initial effective stress (σ'_i), undrained shear strength (s_u), initial tangent modulus (E_i), secant stiffness at half of the peak deviator stress (E_{50}) and Skempton's pore pressure parameter A at peak deviator stress (A_p) while the value of axial strain at peak deviator stress (ε_p) increased due to disturbance.
2. It was found that the nature of the effective stress paths of the normally consolidated "tube" samples were markedly different from that of the respective "in situ" sample. However, the nature of the effective stress paths of the overconsolidated "in situ" and "tube" samples were, in general, similar.
3. Compared with "in situ" samples, the pore pressure changes of the "tube" samples are significantly less, resulting in much lower values of A_p for the "tube" samples than those of the "in situ" samples. The values of A_p of the "tube" samples were found to be negative.
4. The results indicated that compared with normally consolidated reconstituted Dhaka Clay, tube sampling caused relatively little degree of disturbance in overconsolidated reconstituted Dhaka Clay.
5. Changes in undrained soil parameters between the "in situ" and "tube" samples were found to depend significantly on the design of sampling tube. The higher the area ratio and OCA of sampler, the greater is the reduction in σ'_i, s_u, E_i, and E_{50}. Values of ε_p however, increased with increase in area ratio (or decrease in D_e/t ratio) and increase in OCA of sampler.
6. The quantitative values of degree of disturbance (D_d) of "tube" samples increased significantly with the increase in area ratio (or decrease in D_e/t ratio) and increase in OCA of sampler.

6.1.2 INVESTIGATION OF THE EFFECTS OF PERFECT SAMPLING DISTURBANCE IN DHAKA CLAY

Influences of perfect sampling disturbance on undrained stress-strain-strength, stiffness and pore pressure characteristics have been investigated for reconstituted normally consolidated and overconsolidated samples of Dhaka clay. The main findings and conclusions are as follows:

1. The nature of the effective stress path of the normally consolidated "perfect" sample was markedly different from that of the "in situ" sample. The nature of the effective stress paths of the overconsolidated "in situ" and "perfect" samples, however, were similar.
2. Disturbance due to perfect sampling led to reduction in the values of s_u while the values of E_i, E_{50} and ε_p increased because of disturbance due to total stress relief.
3. Compared with "in situ" samples, the pore pressure changes of the "perfect" samples are very small, resulting in much lower values of A_p for the "perfect" samples than those of the "in situ" samples.

6.1.3 INFLUENCE OF STRESS HISTORY ON TUBE AND PERFECT SAMPLING DISTURBANCE EFFECTS

The conclusions relating to the influence of stress history on tube and perfect sampling are summarised below:

The influences of stress history on tube sampling are as follows:

1. The reduction in σ'_i reduced with the increase in overconsolidation ratio (OCR).
2. Trend of small decrease in the reduction of s_u/σ'_{vc} and E_i/σ'_{vc} with increasing OCR were obtained. However, significant increase in the reduction of A_p with increasing OCR was found.
3. The values of s_u, E_i and E_{50} decreased with increasing OCR. However, the degree of reduction in s_u, E_i and E_{50} with increasing OCR were found to be small.
4. The increase in ε_p reduced with increasing OCR.

The influences of stress history on perfect sampling are as follows:

1. The reduction in s_u increased with the increase in OCR.
2. The increase in value of ε_p increased with increasing OCR.
3. The increase in the values of E_i, and E_{50} reduced with the increase in OCR.
4. The reduction in value of A_p reduced with increasing OCR.

6.1.4 EFFECT OF RECONSOLIDATION OF "TUBE" AND "PERFECT" SAMPLES ON OVERCONSOLIDATED DHAKA CLAY

The conclusions relating to the influence of reconsolidation in "tube" and "perfect" samples of overconsolidated samples of Dhaka clay having OCR values of 2 and 10, are summarised below:

1. Isotropic reconsolidation (CIU-1.0σ'_{vc}), using an effective consolidation pressure equal to σ'_{vc} of the "in situ" sample, had the effect of gross overestimation of "in situ" values of s_u, ε_p, E_i, E_{50} A_p for the "tube" and "perfect" samples for both the OCR values.
2. In contrast to isotropic reconsolidation, for both OCR values, the undrained shear strength ratio (s_u/σ'_{vc}) and stiffness ratios (E_i/σ'_{vc} and E_{50}/σ'_{vc}) of the " tube" and "perfect" samples reconsolidated using Bjerrum (CK$_0$U-1.0σ'_{vc}) and SHANSEP (-1.5σ'_{vc} and – 2.5σ'_{vc}) procedures were, in general, less than those for the "in situ" samples.
3. Despite of both the Bjerrum and SHANSEP reconsolidation procedures provided a lower bound values of s_u/σ'_{vc}, E_i/σ'_{vc} and E_{50}/σ'_{vc}, and an upper bound the value of ε_p and A_p for the "tube" and "perfect" samples than those of the "in situ" samples for both OCR values, the "tube" and "perfect" samples reconsolidated using Bjerrum procedure agreed more closely with those of "in situ" samples for both OCR values.

From the aforementioned findings, it is evident that disturbance due to tube sampling depends considerably on the design of a sampler. For good quality sampling, a sampler ought to have a well combination of area ratio and OCA. In order to minimise disturbance due to sampling in normally consolidated and overconsolidated Dhaka clays, area ratio and outside cutting edge angle of sampler should be kept as low as possible. From practical point of view, the area ratio of a tube sampler should not exceed 10% and the outside cutting edge of a tube sampler should preferably be less than 5°. It has been observed form the present study that strength and stiffness of "tube" samples are always less than those of "in situ" samples. So, from practical point of view, although geotechnical analyses and designs, based on strength and stiffness of soils obtained from laboratory tests of "tube" samples, are on the safe side but it would lead to uneconomic and over design of structures. For optimum and economic design, undrained strength and stiffness parameters of the foundation soils, therefore, should be corrected before being used in the design. In the present research, a correction curve has been developed. This correction curve can be used to find the perfectly undisturbed strength of the tube samples of Dhaka clay for use in analyses and designs.

6.2 RECOMMENDATIONS FOR FUTURE STUDY

Several aspects of the work presented in this thesis require further study. Some of the important areas of future research are listed below:

(1) In this research, reconstituted normally consolidated and overconsolidated samples has been used to investigate the effects of sampling disturbance on mechanical properties in Dhaka clay. This research may be extended using natural undisturbed Dhaka clay to compare the changes in behaviour between reconstituted and intact samples.

(2) Effects of area ratio and outside cutting edge angle of sampler on disturbance have been investigated. Besides this, the effect of other design parameters of tube sampler, on sampling disturbance can be investigated. Such design parameters may include inside clearance ratio, outside clearance ratio, inside cutting edge angle and diameter of the sampler.

(3) In this research, reconstituted Dhaka clay has been used. Similar research can be carried out on normally consolidated and overconsolidated soils collected from different regions of Bangladesh, particularly soils from coastal regions.

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