Investigation of Relationship between Distortion Settlement, Lateral Spreading and Consolidation Settlement of a Selected Cohesive Soil

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ABSTRACT

Long-term settlement of foundation on clay soils is a well-known aspect of geotechnical design. Prediction of the performance of building foundations or embankments can be complicated and expensive in such ground conditions. Construction costs need to be balanced against high maintenance costs considering the long term performance. In order to do this optimally, there is a need to predict long term settlement with reasonable accuracy. For a reasonable prediction of long term settlement, it is crucial that ground investigation, laboratory testing and monitoring of ground settlement during and after construction are carried out. However, in most cases these are not possible to carry out in a project due to various reasons such as; increased construction costs, time and resource limitations etc. Hence, engineers commonly rely on punished empirical data on ground settlement behavior, which may sometimes be misleading.

In order to reduce the cost of obtaining a reasonable prediction of long term settlement, it is proposed that the existence of a relationship between short term or immediate settlement and long term settlement is investigated. Immediate settlement of shallow foundations bearing on clay soils may constitute a significant part of the total settlement. Immediate settlement occurs due to the distortion of cohesive soils in untrained condition also defined as constant volume deformation. As part of this research, two basic mechanisms will be considered; 1- one dimensional consolidation settlement behavior (K=1 loading, in drained condition), and 2- one dimensional distortion settlement behavior (K= variable but controlled, in untrained condition). Two main goal were considered on the settlement behavior investigated using compacted specimens; the immediate settlement behavior and assessment of the relationship between the immediate settlement, consolidation settlement and the total settlement. For the Investigation of one dimensional distortion settlement behavior, a new testing equipment and testing methodology were designed. Experimental findings showed that as the confining stress increases, the immediate settlement indicates descending trend. It was concluded that the ratio of immediate settlement to long term settlement reduces as the value of confining stress increases. The results of this research are in good agreement with those in the literature on the ratio of immediate settlement to long term settlement.

Keywords: consolidation settlement, cohesive soil, immediate settlement, lateral spreading

ÖZ

Geoteknik mühendisliği tasarımında temellerin killi zeminlerde uzun vadede gerçekleşen oturma davranışı iyi bilinen bir konudur. Böyler durumlarda bina veya dolgu temellerinin permormans tahminleri bazen oldukça zor ve masraflı olabilir. İnşaat bütçelerinin uzun vadedeki tamir masraflarını da düşünerek dengelenmesi gerekir. Bu iki unsuru optimize edebilmek için, uzun vadedeki davranışı hassas bir şekilde tahmin edebilmek gerekir. Uzun vadedeki davranışın hassas olarak tahmin edilebilmesi de zemin etüdü, laboratuvar analizleri ve arazide oturma takibi gerektirecektir. Birçok projede bunları gerçekleştirebilmek bazı sebeplerden dolayı mümkün olmayabilir; artan inşaat masrafları, zaman ve kaynak sıkıntıları bu sebeplerden sadece birkaçıdır. Bu nedenle, tasarım mühendisleri genellikle yayınlanmış deneysel veya tecrübeye dayalı verileri kullanmayı tercih ederler ki bunlardan bazıları tasarım hesaplarını yanlış yönlendirebilir.

Uzun vadede gerçekleşen oturmanın daha hassas tespiti için kısa vadedeki oturmanın da iyi incelenmesi ve toplam oturma ile olan ilişkisinin araştırılması gerekmektedir. Kısa vadedeki oturma veya ani oturma, killi zeminlerde inşa edilen temellerin davranışının önemli bir kısmını teşkil edebilir. Ani oturma kohezyonlu zeminlerde drenajsız durumda ve sabit hacim koşulu ile şekil değiştirme (distortion) sonucunda meydana gelir. Bu tezdeki araştırma kapsamında, iki ana mekanizma düşünülmüştür; 1- bir boyutlu konsolidasyon oturma davranışı (K=1 yüklemesi, drenajlı durumda), ve 2- bir boyutlu şekil değiştirme sonucu oluşan oturma davranışı (K= değişken ancak kontrollü, drenajsız durumda). Bir boyutlu şekil değiştirme sonucu oluşan oturma davranışını incelemek için yeni deneysel metodoloji ve buna bağlı olarak

ekipman oluşturulmuştur. Sıkıştırılmış numuneler üzerinde yapılan deneyler sonucunda oturma davranışı incelenmiş ve iki temel hedef belirlenmiştir; ani oturma davranışı ve ani oturma ile uzun vadede oturma davranışı arasındaki ilişkinin değerlendirilmesi. Deneysel çalışmalar göstermiştir ki, zemindeki çevresel efektif basınç yükseldikçe ani oturmada bir azalma elde edilmektedir. Ani oturmanın uzun vadedeki oturmaya oranı değerlendirildiğinde bu oranın çevresel efektif basınç artarken azaldığı bulunmuştur. Bu tezdeki deneysel sonuçların literatürdeki benzer diğer araştırmalar ile uygun sonuçlar verdiği gösterilmiştir.

Anahtar kelimeler: ani oturma, kohezyonlu zemin, konsolidasyon oturması, yanal şekil değiştirme.

to

MY Parents

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LIST OF SYMBOLS

C_c	Compression index
C_s	Swelling index
C_v	Coefficient of consolidation
G_s	Specific gravity
K	Hydraulic Conductivity
CH	Highly Plastic clay
W_{op}	Optimum Moisture content
σ	Normal stress
$\Delta\sigma$	Axial stress increase
σ_3	Confining stress
σ_1	Total Stress
Δu	Pore water pressure
P_s'	Swelling Pressure
ε_{ai}	Axial strain (Immediate settlement)
ε_{ac}	Axial strain (consolidation Settlement)
σ_p'	Induced Preconsolidation pressure
S_i	Immediate settlement
S_c	Consolidating Settlement
σ_v'	Effective stress
c_u	Undrained shear strength
γ	Poisson's ratio
q	Net applied pressure at the base of foundation
E_u	Modulus of elasticity in the undrained state

I_p	Influence factor
H_0	Initial Height of soil specimen
Δe	Changing void ratio
e_0	Initial void ratio

LIST OF ABBREVIATIONS

ASTM	American Society for testing and materials
LL	Liquid limit
PI	Plasticity index
PL	Plastic limit
CRS	Constant rate of strain
LP	Loading Path

Chapter 1

INTRODUCTION

1.1 Background

Total settlement of shallow foundations on cohesive soil can be categorized as; the immediate settlement (also termed as undrained or distortion settlement), consolidation settlement and creep settlement. Within these categories, the consolidation settlement, or in other words, long term settlement is considered to take place as drainage occurs upon increase in the applied load and often addressed as the only component of total settlement causing serious engineering challenge in the design of various civil engineering structures in cohesive soil deposits.

The immediate settlement component of the total settlement is described as the elastic deformation of the ground without any volume change occurring, which means distortion of the loaded zone is caused by the foundation load. In this component of deformation mechanism it is considered that the ground deforms without any significant dissipation of excess pore water pressure.

In most cases, the distortion settlement of cohesive soils is assumed to be the minor component of the total settlement (Foye et al, 2008). However, as it was first famously stated by Foot & Ladd (1981) based on experimental studies in the field, the distortion settlement could be significant in highly plastic or organic cohesive soils.

In addition, the immediate settlement is also important where the total settlement (not only the time dependent settlement) is required to be considered. This is usually the case in projects where the total impact of the applied load on a nearby structure or infrastructure is in question.

The distortion settlement is closely associated with the mobilization of the undrained shear strength of the ground against foundation loading, as a result of which, settlement occurs. As the degree of mobilization of the undrained shear strength increases, the undrained response, hence the distortional deformation of the ground increases. Hence, it can be stated that the study of immediate settlement is an integral part of the overall settlement behaviour of foundations (D'Appolonia et al. 1971, Strahler 2012).

1.2 Measurement and Prediction of Immediate Settlement

There are various methods for estimation of the distortion settlement of shallow foundation including perfectly flexible and rigid foundation models. The most popular methods are presented by the following authors: Janbu et al. (1956), Christian and carrier (1978), Harr (1966), Giroud (1968), Bowles (1996), Gazetas et al. (1985) and Mayne and Poulos (1999). However, these don't produce generalized parameters which can be used in the foundation design, but provide results for behavioral studies instead.

In typical geotechnical designs, settlement assessments are carried out based on the results obtained from laboratory or in-situ tests, or monitoring data from site. The experimental methods include standard oedometer test, which is ideal for foundations on cohesive soils. These tests are successfully used in the analysis of long term behavior, without allowance for measurement and quantification of distortion behavior. Therefore, considering that the immediate behavior of cohesive can be significant and may be required to be assessed in the geotechnical analyses prior to assessment of the long term behavior, a reliable measurement method for the study of the quantity of the distortion settlements is also needed.

1.3 Purpose and Scope

The aim of this study is to investigate immediate (distortion) settlement behavior of a selected cohesive soil with moderate to high plasticity. The possibility of existence of a relationship between immediate settlement and long-term settlement is also studied.

The study involved an experimental programme designed to consider measurement of distortion settlement under varying degrees of confinement, i.e. anisotropic stress states. The effect of geometry on the distortion is eliminated by considering a standard oedometer test setup with confinement provided using all round pressure. It is considered that the distortion settlement should be significantly affected by the stress state at which the soil specimen is consolidated. The standard oedometer testing method is modified and a test procedure following a stress controlled approach is developed to test the soil samples at a triaxial stress state.

In this thesis, the results of the experimental research is presented in five chapters. Proceeding the introduction chapter are;

- Literature survey, Chapter 2, which consists a summarial presentation of the past research work on immediate settlement of cohesive soils,
- Chapter 3, Experimenal Methods and Results, presents information about the soil specimen used in this study, the research methodology and the factual results of the tests carried out,

- Chapter 4, Analysis and Discussion of the results, which consists detailed analysis of the data, comparative curves, and thorough evaluation of the relationship between immediate and consolidation settlement,
- and finally Chapter 5, which presents summary conclusions of this research work and recommendations for further studies.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

The general response of a material when subjected to stresses is deformation, or in other words, strain. Sometimes the response of a material is instant (immediate), as in elastic behavior. Cohesive and impermeable soils demand a comparatively long time for the deformations to occur. This is caused by the delay in the mobilization of their effective shear resistance due to their low permeability. In such soils, deformation occurs as a result of change of volume (compression) and change of shape (distortion), or both (Holtz et al., 1981). Soils are extremely nonlinear materials. The, interrelationship between stress, strain and time is not simple and cannot be solved easily by mathematical theories. In addition, the problem is worsened by another feature of soils; they have “memory”.

The distortion and compression in cohesive soils occur due to hydraulic and mechanical processes. The hydraulic processes are controlled by water content changes, and mechanical problems are due to vertical stress changes. (S. Bensalem et al., 2014).

2.2 Components of Settlement for Cohesive Soils

A soil deposit deforms when subjected to load with the total vertical deformation at the surface named “settlement”. Moreover, decline in the stress due to interim construction excavations or constant excavations like highway cuts or reduction of water table may also result in settlement.

For cohesive soils, settlement is time- dependent due to low permeability. The total settlement (S_t) for cohesive soils have the following components (Holtz et al., 2011):

$$S_t = S_i + S_c + S_s \tag{2.1}$$

where;

S_i: Distortion or immediate settlement.

S_c: Primary consolidation (time-dependent) settlement.

S_s: Secondary consolidation settlement or creep.

The distortion settlement occurs in the undrained state due to change of shape of the soil as a result of shearing and/or bulging beneath the center of a loaded area. It increases as; the shear strength of the soil decreases and the degree of the mobilized shear stress in the ground increases, (Foot and Ladd, 1981).

On the other hand, primary consolidation settlement is time dependent and occurs based on permeability and drainage conditions in the ground. Drainage leads to effective stress increase and the stress state in the soil changes. Secondary consolidation or creep follows on from the primary consolidation and also occurs under constant effective stress. It is also considered to be proportional to the distortional settlement.

2.3 Elastic Theory Analysis

In elasticity theory, the soil is perfectly elastic and isotropic. In order to calculate elastic settlement the modulus of elasticity, E, which is defined as the linear relationship between the vertical stress increase and axial strain, is used. The Poisson's ratio, ν in undrained condition is considered to be equal to 0.5, and the modulus of elasticity, E_u, for the undrained state is obtained using triaxial test results or correlations available as in Duncan and Buchignani (1976) and Ladd et al (1977).

2.3.1 Modulus of Elasticity

The definition of modulus of elasticity is as the ratio of stress over the strain in the range of elastic soil behavior. The elastic modulus is regularly applied to predict the soil settlement and elastic deformation analysis. The undrained elastic modulus of soil, E_u, can be obtained through laboratory or in-situ tests. There are also correlations available to obtain E_u indirectly such as the one depicted by Kulhawy & Mayne (1990).

$$Eu = K\, c_u \tag{2.2}$$

The undrained elastic modulus is related to c_u in a linear fashion by applying a factor called K, which is given as a variable with respect to the overconsolidation ratio, OCR and Plasticity Index, PI famously presented by Duncan and Buchignani (1976).

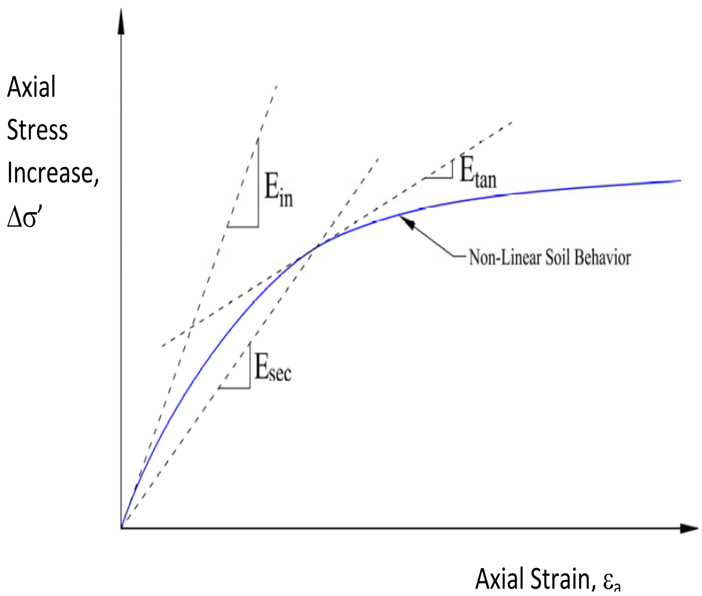

Figure 2.1: Definition of soil modulus from triaxial test results.

2.3.2 Poisson's ratio

For saturated cohesive soil during undrained conditions, the volume change is not expected to occur in the short term, and Poisson's ratio is assumed to be as 0.5. For drained loading an empirical formula for obtaining Poisson's ratio is proposed by Wroth (1975).

$$\nu = 0.25 + 0.00225\,(PI) \tag{2.3}$$

where;

PI: Plasticity index,

ν: Poisson`s ratio.

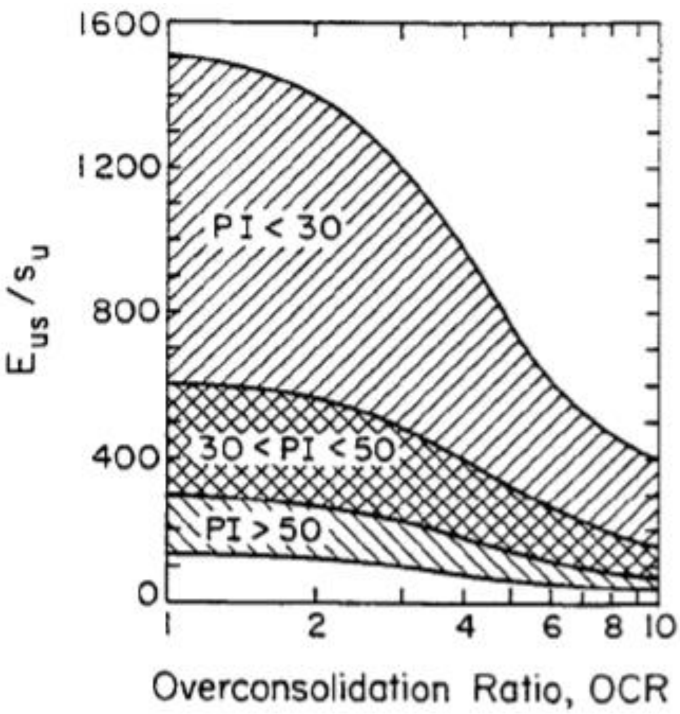

Figure 2.2: Variation in factor K with respect to OCR and PI, (Duncan & Buchignani, 1976).

In Figure 2.2, Su corresponds to undrained shear strength, which is indicated as cu earlier in this section.

2.3.3 Immediate Settlement According to The Theory of Elasticity

The immediate (distortion) settlement can be evaluated simply based on the theory of elasticity as depicted in the following Equation 2.4 as;

$$S_i = q\,B\,I_\rho / E_u \qquad (2.4)$$

where;

q: net applied pressure at the base of the foundation.

E_u: modulus of elasticity of soil in undrained state.

I_ρ : influence factor obtained based on geometry of the problem..

B: smaller dimension of the foundation.

The above relationship doesn't consider any failure criterion for the soil, however, with careful selection of the undrained elastic modulus, it can be applied to account for the utilized undrained shear strength. The influence factor can be evaluated based on an undrained Poisson's ratio of 0.5 and the geometry of the problem, such as proximity of the loaded area or foundation to the hard stratum.

2.4 One Dimensional Consolidation

One dimensional consolidation behaviour of saturated cohesive soils is best described by Terzaghi's theory. In this theory, pure one dimensional compression is considered without lateral deformation of soil and settlement occurs in vertical direction, modelling behaviour of soil beneath the center of a foundation.

The Standard Oedometer test is used to study the one dimensional settlement behavior of cohesive soils, in which a rigid ring confining the soil specimen is used to restrict the lateral deformations as an axial stress increase is applied to the soil specimen. The secondary consolidation can be obtained from the same test by studying the axial compression data under constant effective stress with respect to time. Considering Terzaghi's one dimensional consolidation theory, the following equation can be used for calculating the primary consolidation settlement in a single compressible layer of soil.

$$S_c = \Delta e \, H_0 / (1+e_0) \tag{2.5}$$

where;

e_0: is the initial void ratio.

Δe: change in void ratio for an effective stress range.

H_0: is the initial height of the compressible layer.

The above equation can be generalized for virgin compression behavior of soils, considering normally consolidated clays, by defining Δe in terms of the effective stress on a semi logarithmic plot of void ratio versus effective stress. In that case, the slope of the virgin compression line is called compressibility index, C_c.

2.5 Strain Rate Effects

It is a general belief among geotechnical engineers that one of the clear characteristics of clayey soils is their strain rate dependence. The effect of strain rate is studied by various researches such as; Suklje (1957), Crawford (1964), Sällfors (1975), Leroueil et al. (1985), and Claesson (2003).

Jia, et al. (2010) carried out one of the recent studies on consolidation behavior of Ariake clay. In that study, a sum of 114 constant rate of strain (CRS) consolidation tests and 15 incremental loading (IL) consolidation tests were carried out using undistributed samples. The CRS test device used was comprised of an axial displacement control and back-pressure system. The drainage was permitted only at the top surface of sample. The axial displacement, axial load and excess pore water pressure beneath the sample were recorded.

The outcome of the study showed that the consolidation yield stress of Ariake clay was enhanced by about 15-16% when a tenfold increase in strain rate was attained. It was also observed that, under a given effective vertical stress, coefficient of consolidation, C_v increases with the increase of the strain rate. The CRS oedometer tests were generally performed with a strain rate of 0.02% per minute.

Mats Olsson (2010) have carried out a considerable number of consolidated-undrained triaxial compression tests on compacted low plasticity clay in the saturated and unsaturated condition. One of the main aim of this study was to consider the effect of strain rate on the undrained shear strength of clay. The outcome of their study demonstrated that the undrained shear strength of saturated compacted clay increases with the increase in the strain rate.

Furthermore, Jenn and John (2014) also found that with the increase in the rate of strain, the undrained shear strength of unsaturated compacted clay increases. It is considered that the increase in the undrained shear strength is closely related to the distortion settlement, such that they are indirectly proportional, and therefore an increase in the strain rate is likely to cause decrease in the distortion settlement.

2.6 Temperature Effects

Temperature is one of the main factors that control the geotechnical properties. This impact has attracted the attention of many researches like Campanella & Mitchell (1968), Tidfors (1987), Tidfors & Sällfors (1989), Eriksson (1989), and Boudali et al. (1994). A study is carried out to investigate the effect of temperature on consolidation characteristics for a temperature range from 5°C to 40°C by modified oedometer test. As it shown in the Figure 2.3, it is recorded from the results of the study that there is an increasing trend in the preconsolidation pressure, P_{ac}, and compression index with the increase in temperature, where H is the height of sample. It should be mentioned that this trend is more prevalent for P_{ac} compared to C_c (Mon et al. 2014).

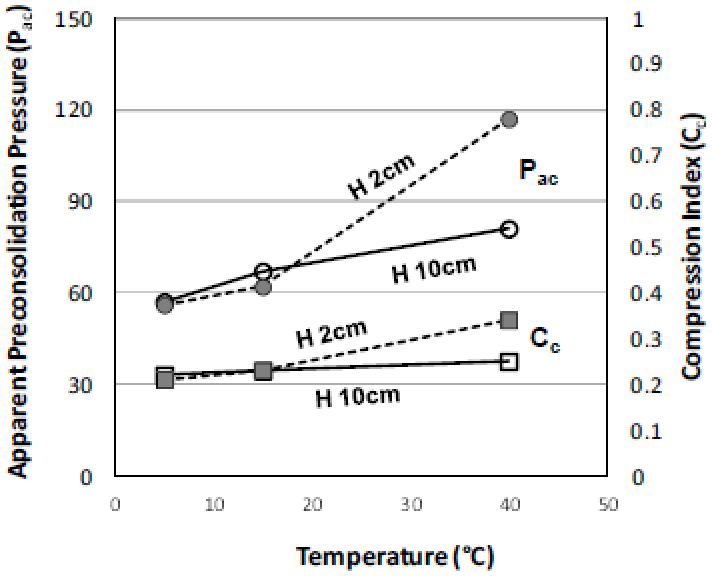

Figure 2.3: Effect of temperature on apparent preconsolidation pressure and compression index, (Mon et al. 2014).

On the other hand, in a laboratory study conducted by Tidfors (1987), presented in Figure 2.4, the the trend of Pac with respect to temperature is opposite. The justification of this difference in the results can be based on the previous research by Crawford (1964), which describes the effect of temperature on preconsolidation stress as very sensitive to the technique of testing. The reason of this opposite trend may be related to the diversity of the sample properties such as void ratio or clay fabric structure, duration of heating or cooling, applied preconsolidation etc.

The overall conclusion is that, the compressibility characteristics such as P_{ac} and C_c

are affected from temperature. The improvement in the consolidation characteristics and the rate of consolidation means that the undrained response of the soil will also be improved, hence it can be stated that a temperature increase is likely to lead to a smaller distortion settlement and a shortened period within which the undrained response will be observed.

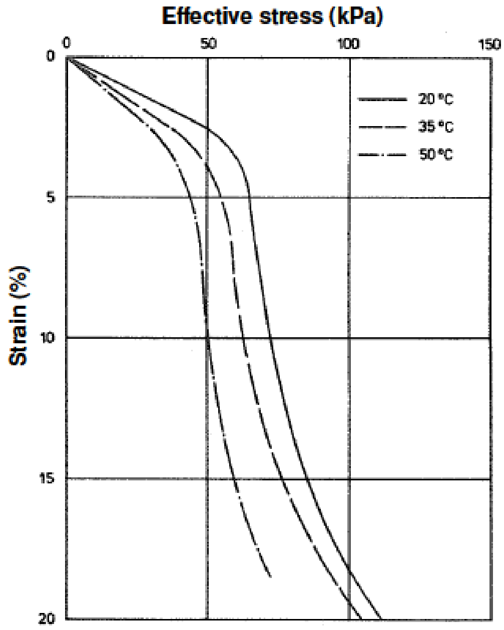

Figure 2.4: Effect of temperature on preconsolidation stress (Tidfors, 1987)

2.7 Settlement of Cohesive Soil

There is a vast amount of research work published on the settlement of cohesive soils In this section a summary of a few selected studies is presented.

The standard oedometer test is traditionally carried out following a stress controlled method, however, towards the end of the twentieth century it has been quite popular with the researchers to study various ways of carrying out the standard oedometer test in an accelerated fashion. The recent studies applying this principle are mainly focusing on application of the load in a strain controlled manner (Smith and Wahls

1969, Lee 1981, Lee et al. 1993, Sheahan and Watters 1997, Ozer et al. 2012, Kassim et al. 2015).

In a recent research work by Kassim et al (2015), a laboratory study is carried out to develop a new testing equipment called; Rapid Consolidation Equipment (RACE). The main achievement of this equipment compared to other strain controlled testing apparatus is the modification, which permits a back pressure to be applied to the specimen for saturation prior to the application of axial stress increase. Typical results obtained on the relationship between void ratio and effective stress are presented in Figure 2.5. In this example, the strain rate used in testing was varied in the range from 0.030 mm/min and 0.061 mm/min. Results are considered to be comparable to the results from a standard oedometer test.

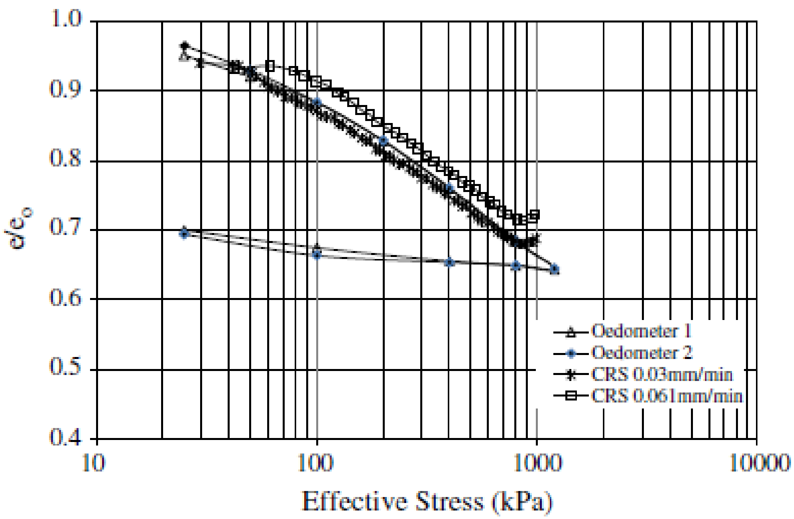

Figure 2.5: The relationship between e/e_0 and log effective stress (Kassim 2015).

An experimental research on the effect of confining stress on settlement and bearing capacity of a circular model footing on silty sand is conducted by Gupta (2009). The impact of geometrical aspects of the laboratory model and fines content of the soil specimen on bearing capacity and settlement are also taken into account in their investigation. The outcome of the study shows that, the bearing capacity of circular footing drops and the settlement at a particular load increases with increasing fines content. It can also be seen from the results that, increase in the confining stress reduces the settlement significantly.

In a recent study by Vanapalli & Mohamed (2013), the impact of matric suction and effective overburden stress (in other words confining stress) on bearing capacity and settlement behavior of saturated sand is investigated using laboratory model footing tests.

In the above study, the variation of matric suction with respect to the depth in unsaturated area of the test box is measured by a tensiometer. The results of the study showed that bearing capacity and settlement are significantly affected by matric suction and confining stress, such that the settlement is reduced with increase in matric suction and overburden stress as plotted in Figure 2.6, Vanapalli & Mohamed (2013).

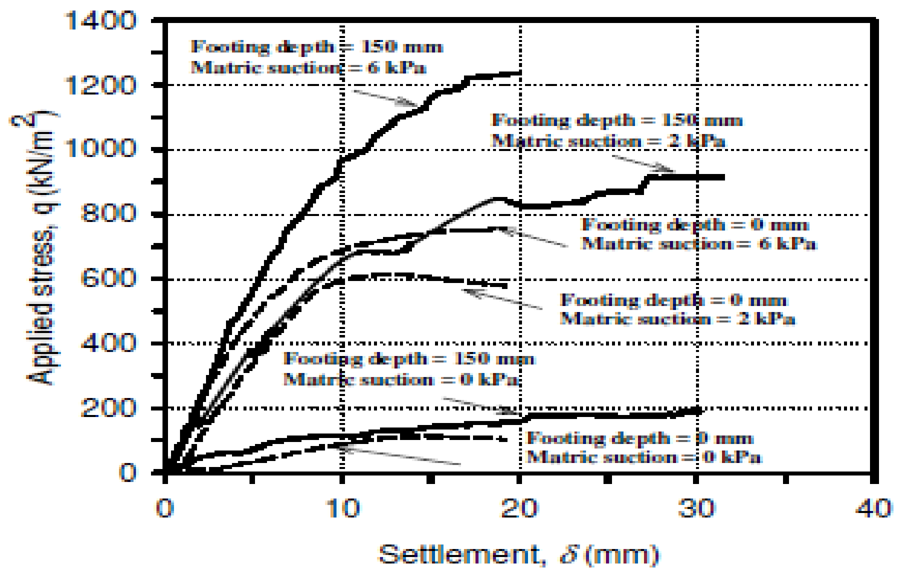

Figure 2.6: Relationship between the applied stress versus settlement behavior of surface and embedded model footing tests (Vanapalli & Mohamed, 2013).

2.8 Settlement of Highly Plastic Clay

The settlement behavior of clays with high plasticity requires special attention in the sense that, as the plasticity of clays increase it is expected that the compressibility and the overall volume change potential of the clay also increases.

In a recent study by Bensallam et al. (2014), the compressibility characteristics of a plastic clay soil is studied in the laboratory and by in-situ tests. In this study, the cyclic response of the plastic clay against wetting drying cycles and load-unload cycles, which indicated that there is a dampening effect of the cycles on the axial deformation of the soil. The soil deformation is reported to be almost independent of the initial condition of the soil after approximately three cycles.

Tiwari & Ajmera. (2011), carried out a study to investigate the effect of mineral composition and initial moisture content on the compression index of clays. Fifty five soil samples comprised of montmorillonite, kaolinite, illite and quartz are prepared in the laboratory at an initial moisture content equivalent to their liquid limit. The soil samples are then subjected to standard oedometer test at an effective vertical stress regime of; 24, 48, 96,192,384,768 and 1536 kPa. The outcome of this research shows that each kind of clay mineral combination has its own intrinsic compression line and the curve of consolidation and swelling for montmorillonite is sharper than those achieved for kaoline and illite (Figure 2.7). Moreover, it is found that the consolidation and swelling behavior of kaolinite and illite are similar.

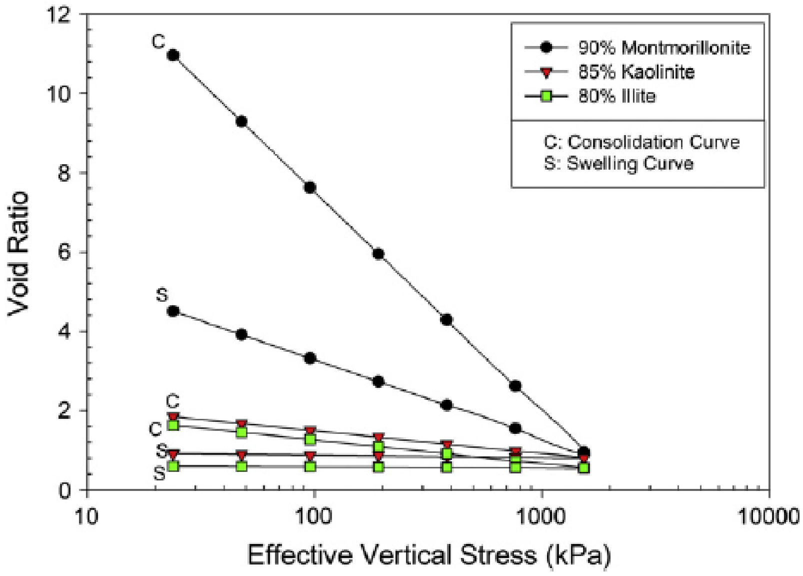

Figure 2.7: e–σ_v' curves for montmorillonite, kaolinite and illite.

2.9 Factors Affecting Settlement

One important factor having a considerable impact on the rate of settlement is drainage. When an incremental stress applied to the layer of clay soil, the dissipation of excess pore water pressure starts to happen slowly due to low permeability of this type of soil. This means that settlement occurs gradually over a long period of time because of the dissipation of excess pore water pressure in voids within the soil. There are various other factors which affects compressibility as listed in the following text;

- Initial conditions prior to load application such as, initial density and void ratio, water content, preconsolidation pressure, stress state,
- Plasticity and Mineral structure of the soil,
- Soil classification, fines content,
- Temperature of the pore water affecting viscosity and settlement rate rather than magnitude,
- Rate of load application,

- Nature of the applied load and geometry of the loaded area,
- Other factors.

2.10 Consolidation of Clay in a Flexible Ring in Oedometer

In 1919, Terzaghi produced the first oedometer, demonstrating the principle of effective stress, and the amount and rate of settlement was first assessed at that time. Since then, there have been numerous developments regarding laboratory testing of the compressibility behavior of soils. Venkatramaiah (1993) stated that one of the modifications that needed to be considered for oedometer test results is the allowance for lateral strain, as a rigid ring is used in oedometer device restraining the sample to deform laterally, which is not an accurate representation of the field conditions.

Kang and Shackelford (2009) conducted a study using a flexible-wall cell under closed-system boundary conditions to address the above stated modification. In their study, they claimed that the flexible ring provides full control on the state of stress in the test sample and allowance for application of a back pressure for saturation was also considered. However, they didn’t carry on to complete their testing methodology to account for the axial deformation versus increase in effective stress relationship in their study.

The existing information in the literature about flexible wall testing of soils in the laboratory is limited to triaxial testing or similar, in which the load is applied in a strain controlled manner with allowance for shear deformation as the primary point of interest in this type of testing.

2.11 Measurement of Immediate Settlement of Clay in the Laboratory

The distortion settlement of clay soil is traditionally obtained using analytical ways by employing theory of elasticity. The analytical methods mainly use undrained shear strength and elastic modulus of clay measured in the laboratory as the primary inputs as presented earlier in this chapter.

Preferably, the sample experimented in laboratory should be undisturbed and the quality of the sample is important to gain a reliable result. Laboratory test designation of the accurate magnitude of equivalent Young‘s modulus Eu (an undrained modulus) is very tough. For this reason, field plate bearing test (ASTM D1194) are usually done for vital projects. In addition, due to the current difficulties to obtain the appropriate result of Eu, Perloff (1975) represented a suitable way to get an equivalent field modulus. Moreover, Simon and Som 1970, conducted a number of case histories in normally and over consolidated clays and the following ranges for initial and total settlement were observed that the ratio of initial per long term settlement is 0.315-0.735 (over consolidated clay) and between 0.077-0.212 for normally consolidated clay (Bell, 1981).

Chapter 3

MATERIALS, METHODS AND RESULTS

3.1 Introduction

In this chapter, the materials and methods used to study to obtain a relationship between immediate and long term settlement of highly plastic clay are presented.

3.2 Soil Specimen

The soil specimen used in this study is classified as an expansive clay, sampled from behind of Sports Stadium at Eastern Mediterranean University, Famagusta, North Cyprus. The approximate position (Latitude 35.164449 and Longitude 33.878993) of the sampling location is presented in Figure 3.1.

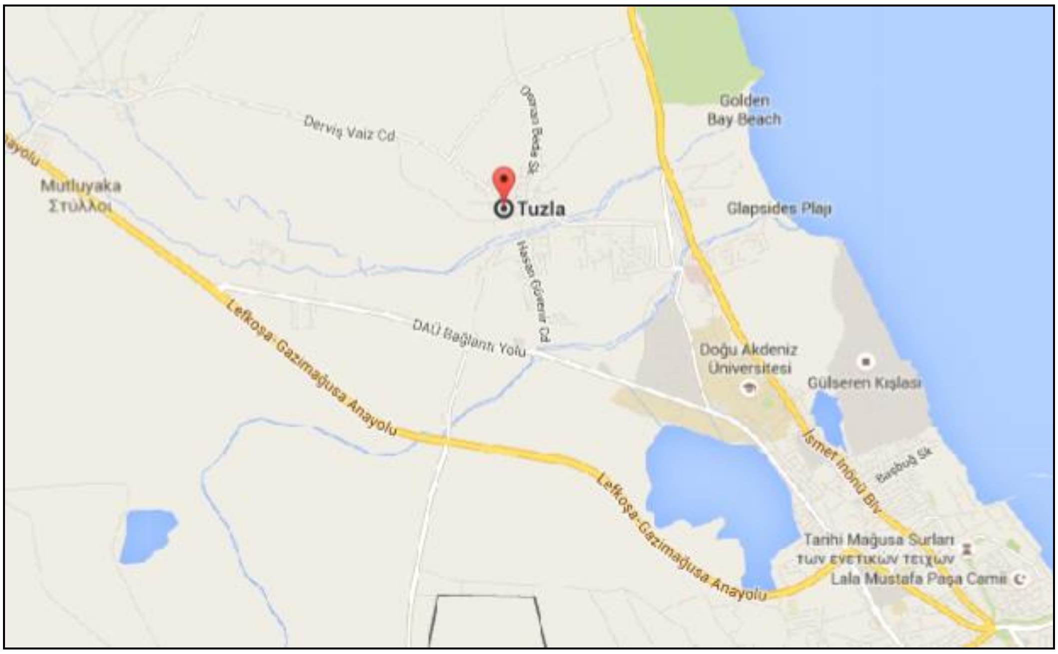

Figure 3.1: Approximate position of the sampling location.

A testing program is conducted to obtain the physical properties and classification of the soil specimen as well as one dimensional consolidation characteristics for samples compacted at maximum dry density and optimum water content. All laboratory tests are conducted in accordance with the standard procedures in American Society for Testing and Materials (ASTM). In addition, a new methodology is developed for testing of immediate (distortion, undrained or elastic) and long term (drained with distortion) settlement behavior of clay under various stress paths (LP-1, LP-2, LP-3 and LP-4).

3.3 Testing Strategy For Measurement of Settlement Behavior

In order to classify the clay samples based on their compressibility characteristics, standard one dimensional consolidation tests are carried out, which allows for measurement of one dimensional settlement in a rigid fixed-ring oedometer. However, the actual behavior of the ground under a similar loading in the field will differ due to variation in the two main mechanisms summarized in the following;

- boundary conditions; as the point of interest for determination of compressibility characteristics is moved away from the center of the point of application of the applied load distortional displacements becomes significant in the undrained condition.
- the state of stress in the ground; the mobilization of the shear stress in the undrained state and the lateral confinement at the point of interest will impact how the ground will respond to the applied load.

As discussed in Chapter 2, traditionally the immediate settlement is calculated based on the undrained modulus obtained from undrained triaxial tests and theory of elasticity. However, triaxial tests incorporate high shear deformations during testing and therefore, does not allow for measurement of pure soil compression as in the case of one dimensional consolidation tests, and it is obvious in the latter test method that drainage conditions and lateral deformability cannot be accounted. Hence, it is considered that for the evaluation of the total settlement characteristics for compression only, one should measure both the deformability in the undrained state as well as in the drained state and in a condition where shear stresses developed are not significant with respect to axial stress increase.

Considering the above, the compressibility behavior of the selected clay sample is tested using three testing methods, namely; standard oedometer tests, modified oedometer for immediate and long term settlement tests, controlled rate of strain tests. The testing strategy is illustrated in the following Figure 3.2.

3.4 Methodology Developed for Testing of Immediate and Consolidation Settlement

A new test method is developed to investigate immediate compression behavior of saturated clay consolidated at various effective stress levels. Thin cylindrical samples of compacted clay placed in a flexible enclosure are first consolidated in a triaxial cell under all round pressure and then subjected to a stress controlled axial loading in undrained condition. Hence, the methodology is similar to a consolidated undrained (CU) triaxial test in essence, however allows for axial, stress controlled loading with negligible shear stress formation due to sample geometry, and measurement of axial compression behavior under a controlled constant confining pressure. In this way, it is considered that the immediate compression of saturated clay can be studied for various stress states and the results can be compared with standard drained one dimensional oedometrer test results, in which sample distortion and variation in conf-

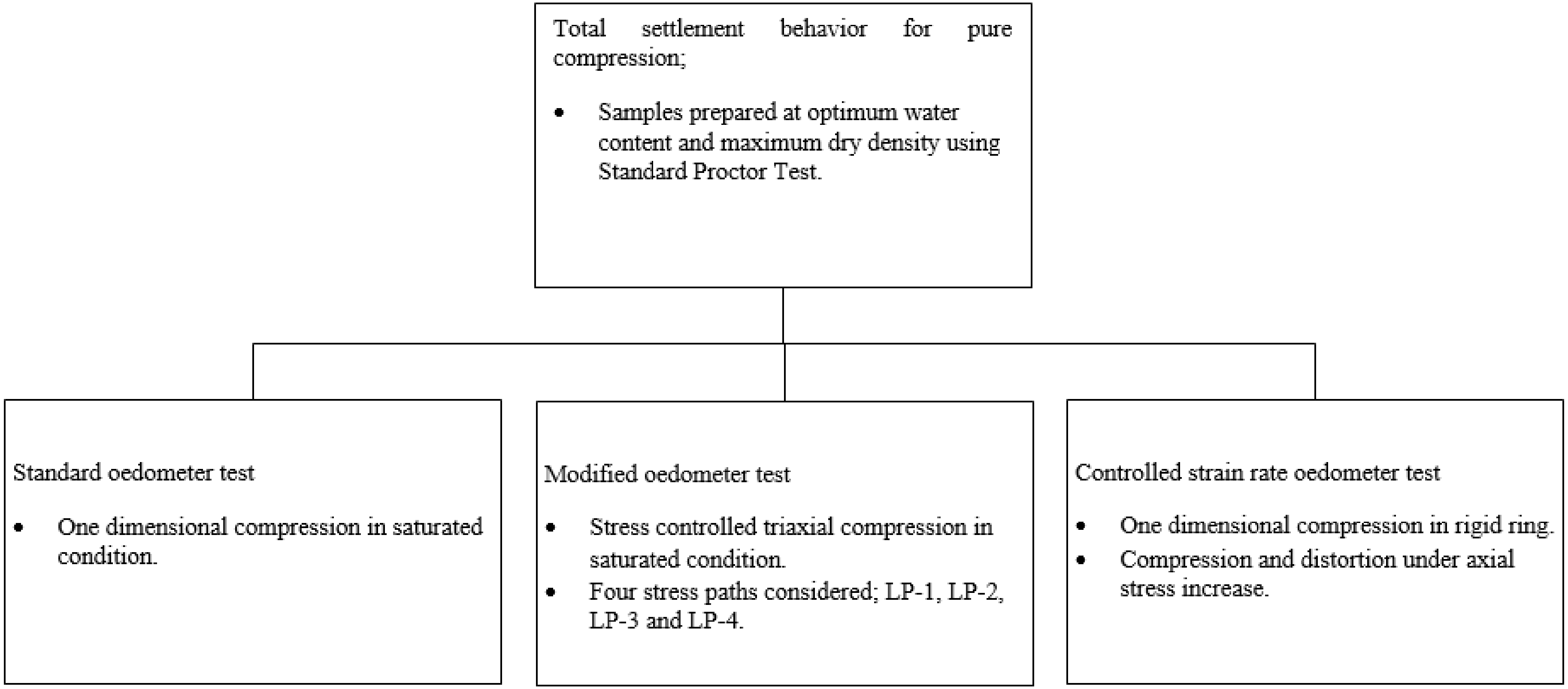

Figure 3.2: Schemmatical representation of testing strategy.

-ining stress are not allowed. The following test groups and four different loading paths are studied in the testing programme;

- Test Group

Four test groups are formed based on the loading path applied during testing. The sample is considered to be loaded in a triaxial state, hence the free body diagram of the sample during testing can be represented as shown in Figure 3.3.

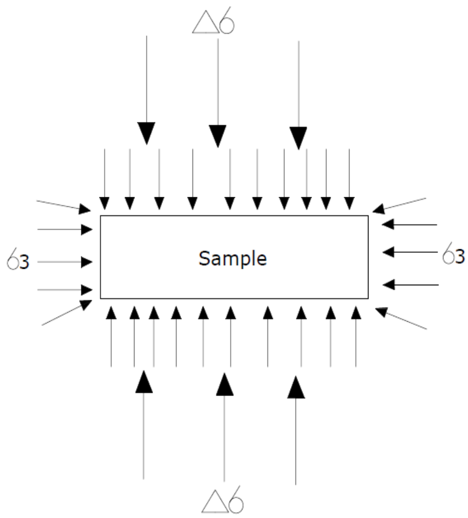

Figure 3.3: Free body diagram of the specimen subjected to triaxial stresses.

The loading path applied in testing is determined using the following method:

$\sigma_1=\sigma_3+\Delta\sigma$ (3.1)

$LP= (\sigma_1-\sigma_3) / (\sigma_1+\sigma_3)$ (3.2)

where;

σ_3: confining stress,

$\Delta\sigma$: axial stress increase.

- **Test Loads and Loading Paths**

The following test loads are applied during testing;

Table 3.1: Axial stress and confining stress applied to the specimen.

Axial stress (kPa)	Confining Stress (kPa)			
	L.P-1	L.P-2	L.P-3	L.P-4
10	5	7.5	10	15
20	10	15	20	30
40	20	30	40	60
80	40	60	80	120
160	80	120	160	240
320	160	240	320	480
640	320	480	640	960
320	160	240	320	480
160	80	120	160	240
1	1	1	1	1

The loading paths are also presented graphically in the following figures (Figure 3.4 to Figure 3.7) in two dimensional stress path plots assuming that the lateral stressess are equal.

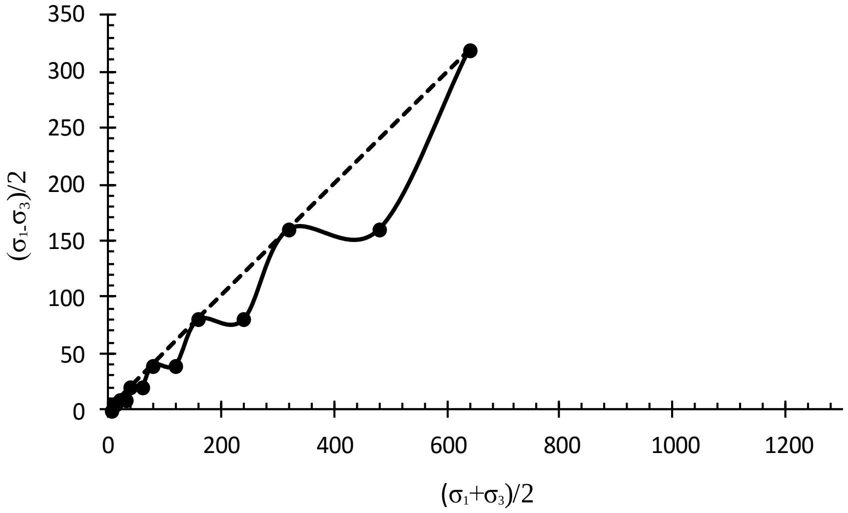

Figure 3.4: Loading path LP-1.

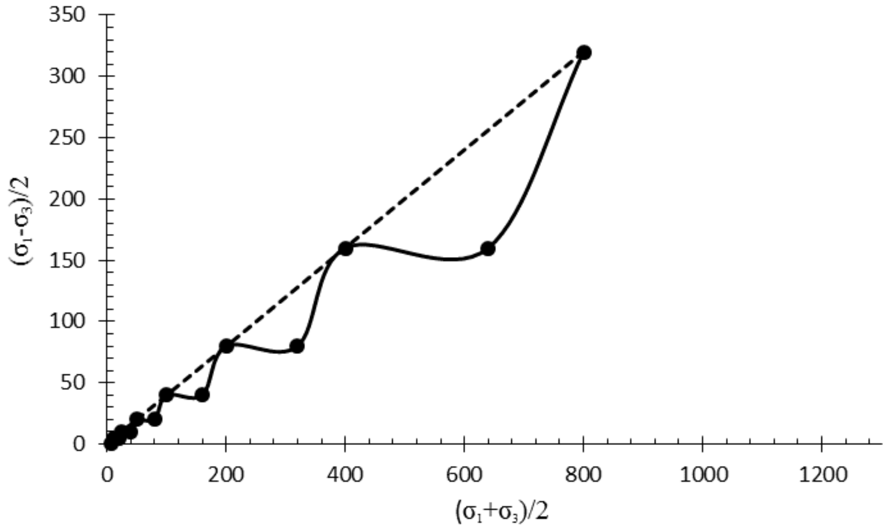

Figure 3.5: Loading path LP-2.

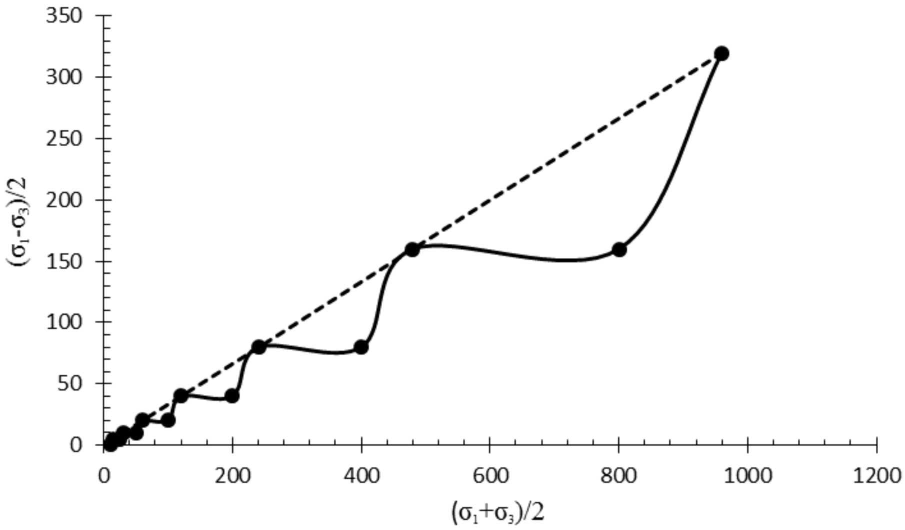

Figure 3.6: Loading path LP-3.

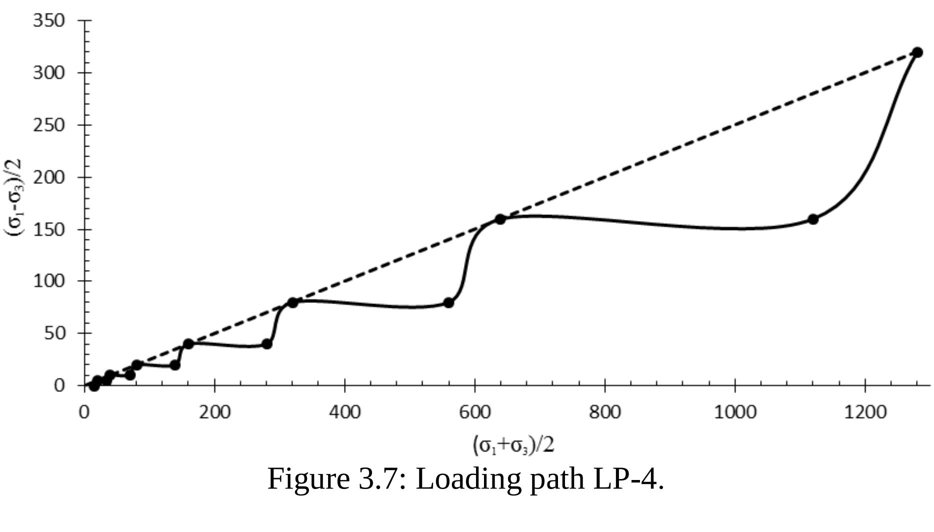

Figure 3.7: Loading path LP-4.

3.5 Design of Modified Equipment

The existing old triaxial cells and oedometers are modified to develop testing equipment for conducting the stress controlled immediate and long term settlement tests. The major components of the new testing equipment are;

- A triaxial testing cell, with back pressure, cell pressure, pore pressure and drainage lines, porous top and base caps.
- Unit for application of confining stress.
- Measurement unit for pore pressure.
- Burette for applying a small back pressure for saturation of the specimen.
- Standard oedometer for application of axial stress increase.

The standard triaxial cell is modified to fit on the loading frame of the oedometer\ while at the same time the loading frame of the oedometer is also modified to cater for the minimum height required for the cell. The base of the cell is adjusted to allow for testing a specimen of 50mm in diameter and 14mm in height. The triaxial cell is checked that a maximum of 640 kPa cell pressure can be applied safely.

Porous stones are used on the top and base of the specimen to provide double drainage conditions during load application, and the specimen is placed in a flexible enclosure. The system allowed to fully saturate the specimen prior to load application with a small back pressure maintained through drainage of distilled water from a burette connected to the top of the specimen by the back pressure line. O-rings are placed to the top and bottom of the specimen to avoid any leakages. The loading Piston of the standard triaxial cell is used to maintain load verticality and to avoid friction between the loading piston and the cell silicon grease is applied. Drainage outlet at the bottom of the triaxial cell and the back pressure line on top are used to control drainage conditions during testing. The secondary outlet at the base of the triaxial cell is used to measure pore pressure at the base of the specimen. Figure 3.8 shows the general arrangement and dimensions of the modified cell.

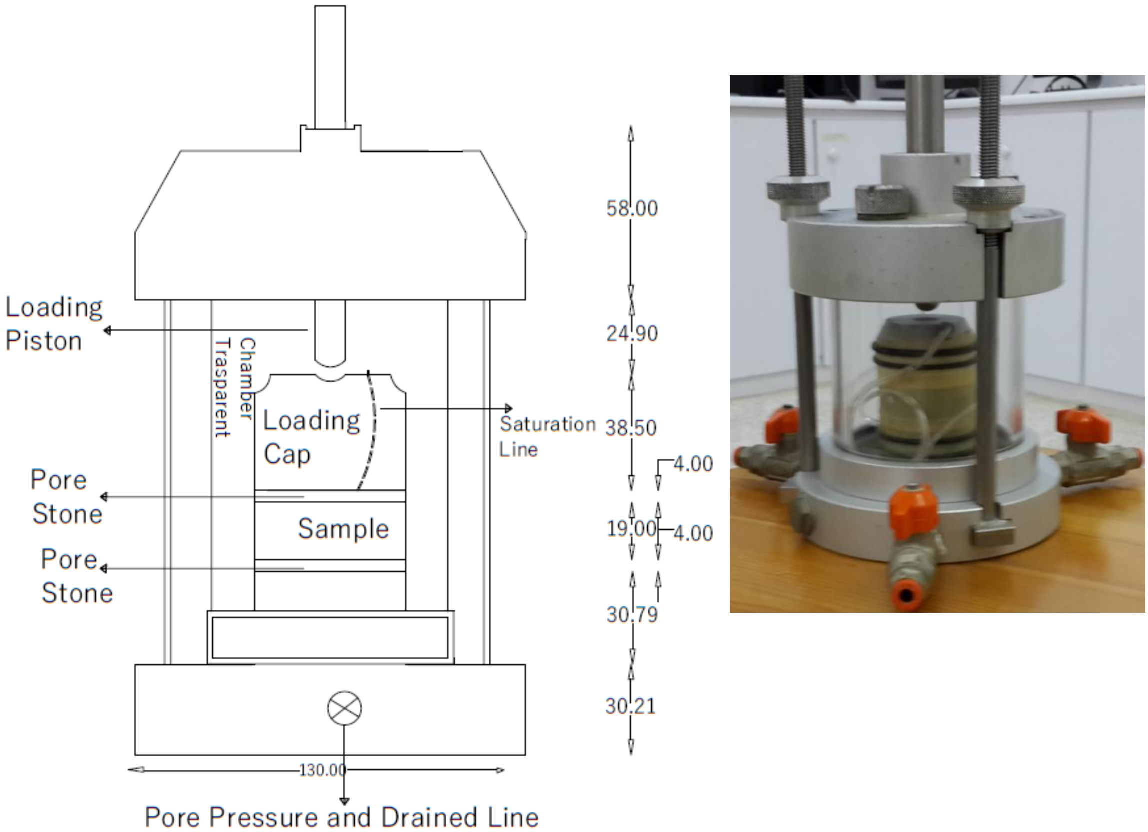

Figure 3.8: The modified triaxial cell (All dimensions are in mm).

- **The Complete Test Setup**

A photo of the complete test setup is presented in Figure 3.9. As the testing is carried out in stress controlled manner, the standard oedometer weights and the cantilever load hanging arm is used. It is considered that 1 kilo pascal placed on the lever arm corresponds to an axial stress increase of approximately 45 kPa. The weight of the loading piston, loading cap and porous stones is considered to be equivalent to an axial stress of approximately 1 kPa.

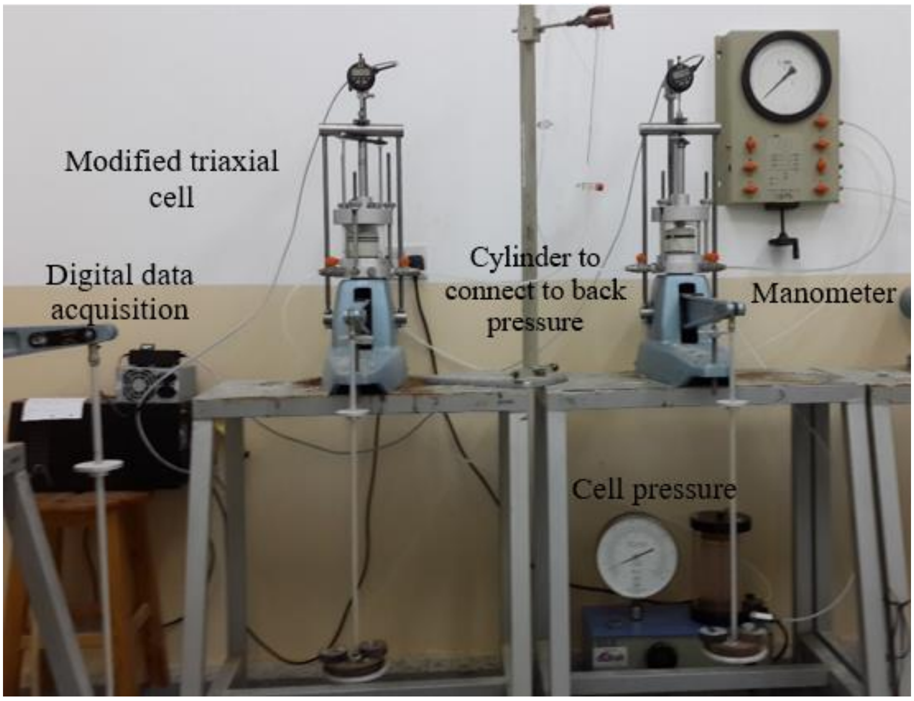

Figure 3.9: Conducting immediate and consolidation settlement in the modified equipment.

A digital logging unit is used to record axial displacement data with respect to a displacement controlled time interval during the test, i.e. after the intial application of the load readings were taken almost non-stop. In addition the recording frequency was based on the change in the axial displacement with an accuracy of 0.001mm. Typical deformation pattern of the samples tested is presented in the following Figure 3.10, with a schemmatical comparison to the deformation pattern of a sample from the standard oedometer test.

Figure 3.10: Typical deformation pattern of the samples tested.

3.6 Detailed Test Procedure Followed for The Modified Test Method

1. Sample is placed in the cell and enclosed with a flexible rubber onto the cell base and a top cap with back pressure system is also attached. After ensuring that the axial displacement gauge is ready, drainage valve is opened and a small back pressure (1 kPa to 1.5 kPa) is applied on top of the sample. The quantities of flow into and out of the sample (if any) are monitored as well as the quantity and rate of swelling. The degree of saturation is calculated using final water content measured from the net quantity of flow into the sample assuming no evaporation loss. It is assumed that the sample is fully saturated after a maximum of three days or when the degree of saturation is 95% or greater.
2. Cell pressure is applied at the desired level and the drainage valve is opened to allow for consolidation of the sample. Dissipation of excess pore water pressures during consolidation is measured using a manometer. This step approximately took 1 day.
3. After completion of the consolidation the drainage valve is closed and the sample is loaded in a stress controlled way by adding weights on the loading arm of the oedometer frame in steps.
4. At each load step, the undrained axial compression due to sample distortion is measured assuming no volume change. After measurement of the undrained axial compression, the drainage valve is opened and the sample is allowed to consolidate, hence allowing for measurement of long term axial compression.
5. Before application of the next load step the drainage valve is closed and steps from 2 to 4 are repeated. The cell pressure increases is calculated for the stress state required by considering a constant ratio of confining stress over axial stress.

3.7 Controlled Rate of Strain Test

In this testing method, the same equipment modified for the immediate settlement measurements is used. Instead of using a stress controlled load application method, the specimen is loaded in a strain controlled manner using the loading frame of the triaxial testing system. The tests are carried out considering two boundary conditions;

- Constrained: the specimen is contained in a rigid ring to attain compression in the axial direction only, and hence without distortion.
- Unconstrained: the specimen is allowed to have lateral deformations as well as axial deformations, confining stress is not allowed.

Considering the above conditions, it is considered that the controlled rate of strain tests (CRS), can provide an upper bound and lower bound compression results which can help justifying the results obtained from the modified oedometer tests, such that;

- the constrained test is likely to yield similar results to the standard oedometer test results and a lower bound compression curve compared to all tests, provided that the loading rate in the CRS test is adjusted so that the test can be carried out in drained condition,
- the unconstrained test is likely to yield an upper bound result considering that confining stress is not applied during testing, hence allowing for the maximum lateral spreading to occur under the same loading range in the other tests.

Based on the standard test procedure given by ASTM (D4186), it can be stated that the test loading rate (strain rate) should be calculated such that the maximum excess pore water pressure at the base of the sample does not increase above 30% of the applied stress increase. However, in this research it is considered that 30% may be excessive, hence the loading rate for a maximum of 10% excess pore water pressure is used. The loading rate used in the CRS tests is calculated as presented in the following:

$$r = \varepsilon_{ac} \times H_o / t_{90} \qquad (3.3)$$

where,

r = rate of strain (mm/min), H_o: initial height of sample (mm), t_{90}: time required for 90% consolidation (min) from standard oedometer tests, ε_{ac}: axial strain for 90% consolidation from the corresponding loading range for t_{90} from standard oedometer tests.

As a result of the above evaluation, a loading rate of approximately 0.015 mm/sec is adopted in the tests.

3.8 Results of Index,Classification Tests and Compaction Characteristics

In this study plasticity tests are carried out to obtain liquid limit and plastic limit of the clay samples. The optimum water content and maximum dry density is obtained using the Standard Proctor Test. Table 3.2 presents the results of the index and classification tests.

Table 3.2: Index and Classification Test Results.

Physical Properties	
Liquid limit (%)	61
Plastic limit (%)	30
Plasticity index (%)	31
Specific Gravity, Gs	2.66
Clay (%)	46
Silt (%)	47
Fine Sand (%)	7

The index tests are repeated several times to improve the accuracy and therefore reliability of the results. It was observed in the plasticity tests that there were significant variations in the results obtained. This is attributed to the expansive character of the samples and it is also speculated that this could be due to the pore water salts and organic material which might have created a temporary change in the behavior of the samples as they were inundated with distilled water.

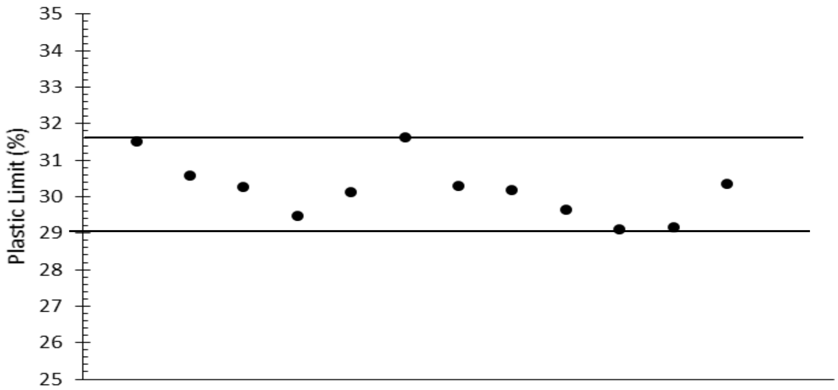

Figure 3.11: Plastic limit test results.

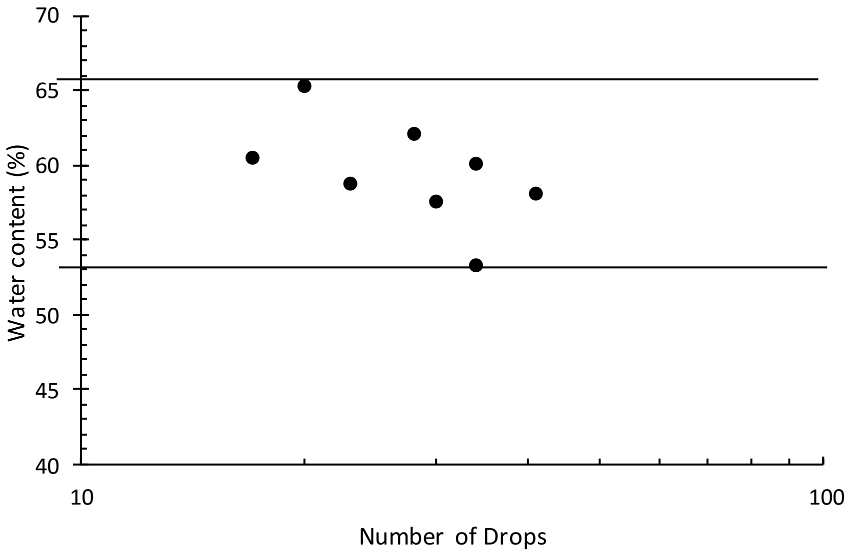

Figure 3.12: Liquid limit test results.

The plasticity tests indicate that the samples have high plasticity with liquid limit greater than 50%.

The results of a selected particle size test is presented in the following Figure 3.13. As it is observed from the typical test results the samples can be classified as fine grained soil with more than 50% comprised of Clay size particles.

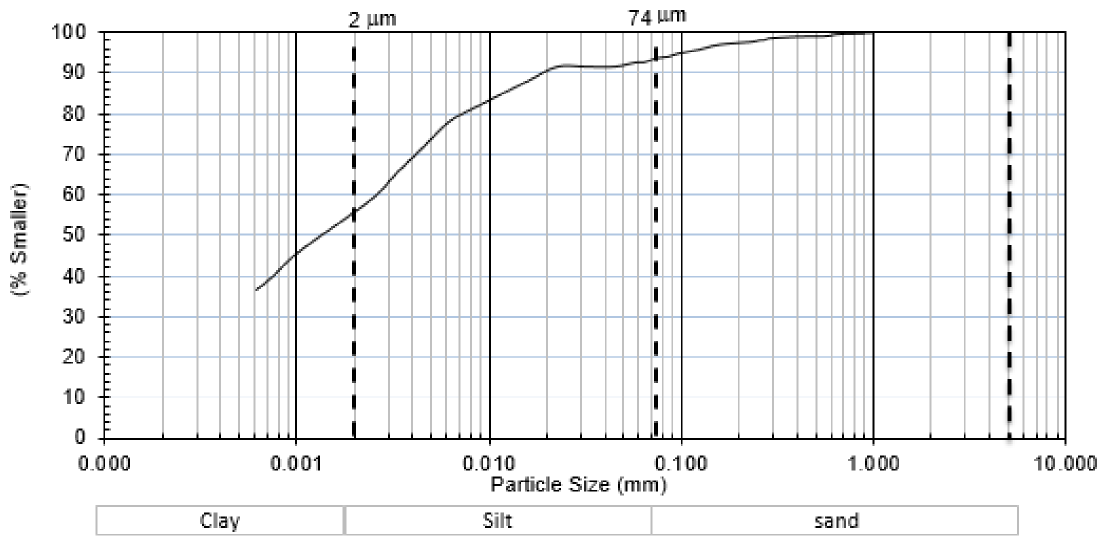

Figure 3.13: Particle size distribution of soil specimen

The overall classification of the samples based on the Unified Soil Classification System (USCS) is determined as CH, corresponding to a ‘highly plastic clay with more than 50% comprised of Silt and Clay.

The standard proctor compaction test results are presented in Figure 3.14. The optimum water content is determined as 27% and the corresponding maximum dry density is calculated graphically as 1.57 g/cm^3.

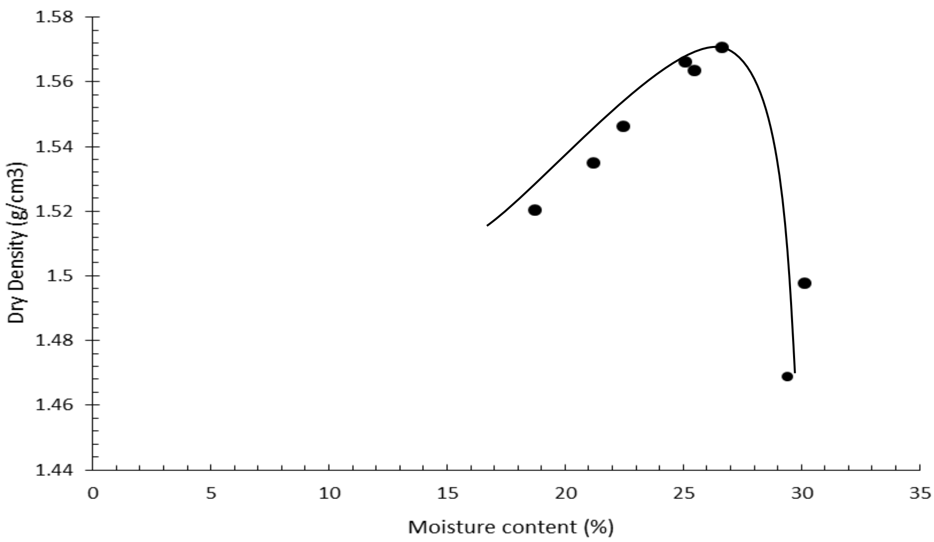

Figure 3.14: The compaction curve of soil specimen.

3.9 Results of Standard Oedometer Consolidation Tests

In the standard oedometer consolidation tests, a set of two soil specimens, with dimensions of 50 mm diameter and 15 mm height, are prepared at the optimum water content and maximum dry density. The specimens were first saturated and left for free swell for a minimum of two days or when the swelling curve is observed to change to a constant slope indicating completion of the ‘primary swell’. It is assumed that at this stage the samples are near to full saturation. The results are used to evaluate the swelling potential of the soil samples.

After the completion of the swelling stage, the samples are subjected to standard loading stages, and the curves of void ratio versus effective stress are plotted to study the consolidation characteristics of the samples. The following parameters are obtained; compression index (C_c), swell index (C_s), swelling pressure (P_s'), induced preconsolidation pressure (σ_p') and coefficient of consolidation (C_v). Figure 3.15 and Figure 3.16 present the average swelling and consolidation behavior of the two same soil specimens.

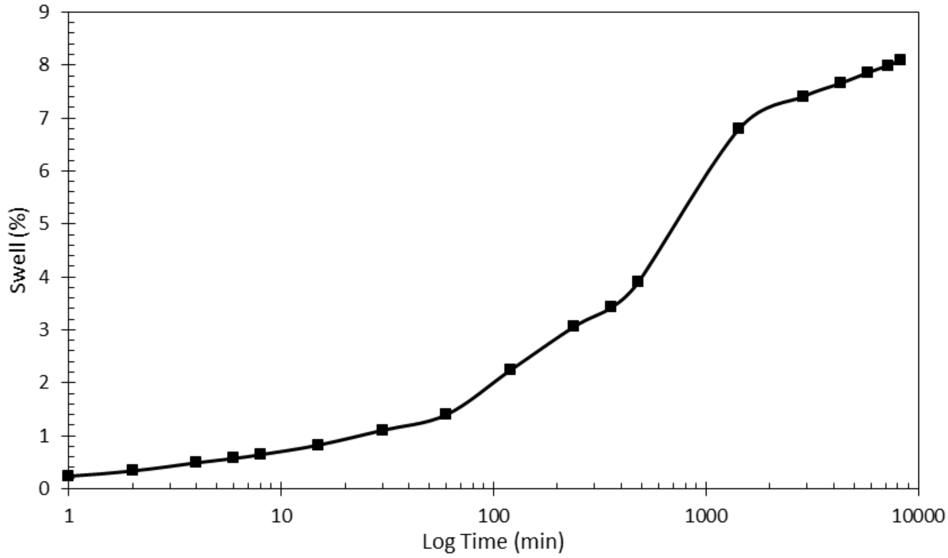

Figure 3.15: Swelling versus time from standard oedometer tests.

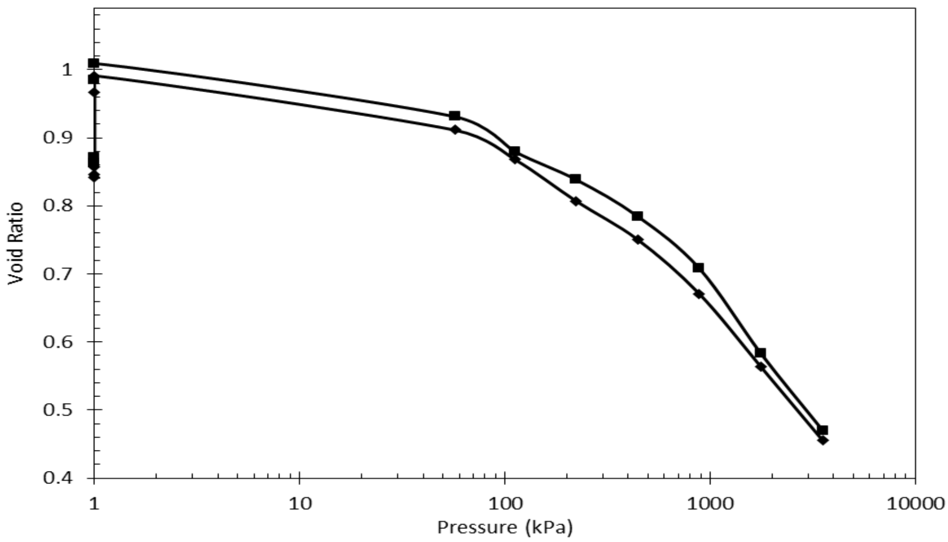

Figure 3.16: Void ratio versus effective stress from standard oedometer tests.

3.10 Results of the Modified Compression Tests

3.10.1 Swelling Stage

In the modified equipment, the swelling stage corresponds to the initial saturation stage of the specimen. The free swell is carried out under a total stress of 2.97 kPa, which is due to the self-weight of the loading piston, the loading cap and the porous stone in the triaxial cell. It was observed from the standard oedometer tests that approximately two days was sufficient for completion of this stage. Figure 3.17

shows the average swell curves obtained from specimens saturated to be tested for compressibility behavior under various loading paths.

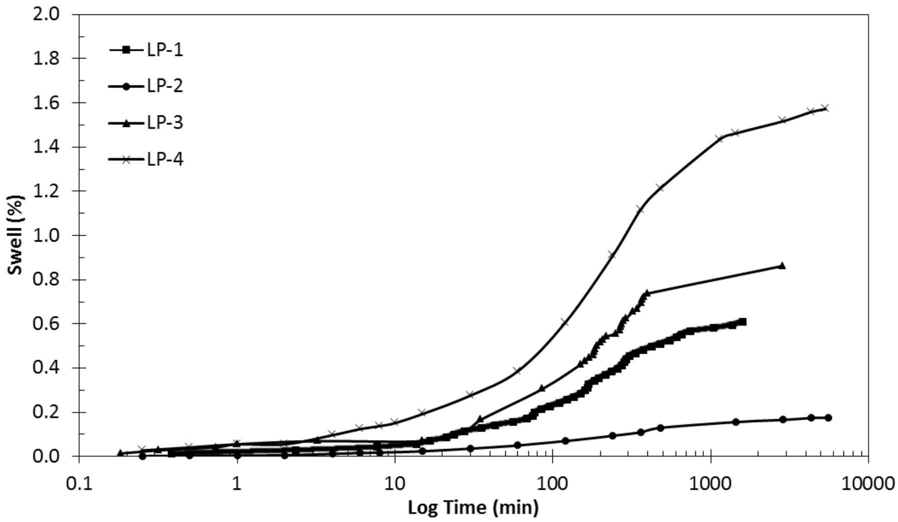

Figure 3.17: The results of swelling stage obtained from the modified equipment.

A comparison of the Figure 3.15 and Figure 3.17 shows that, although the difference in the free swell pressure is minimal (approximately 1.5 kPa), the measured swelling behavior was significantly different. This is considered to be mainly caused by an existing factor;

- The samples were forced to swell in the vertical direction only in the standard oedometer test as opposed to triaxial swell in the modified test.

3.10.2 Immediate Settlement Results

The results of the immediate settlement behavior are presented in Figure 3.18 to Figure 3.21. The methodology included the measurement of the axial displacement readings in the undrained state, until the readings remain constant for a period of 3 minutes, which was typically observed within the first 10 to 20 minutes of the load application.

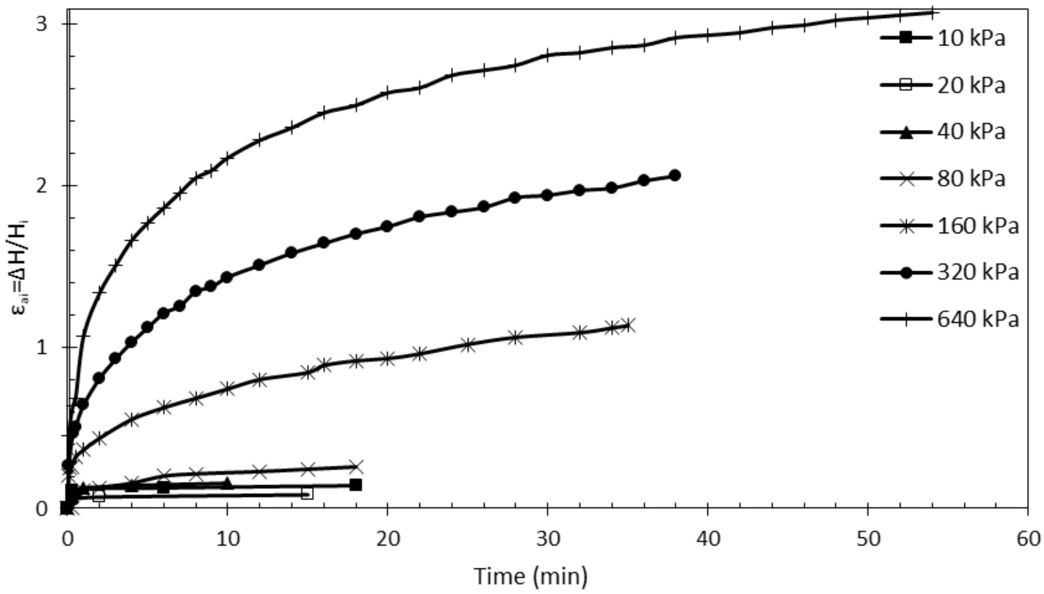

Figure 3.18: The variation of axial strain with time for immediate settlement (LP-1).

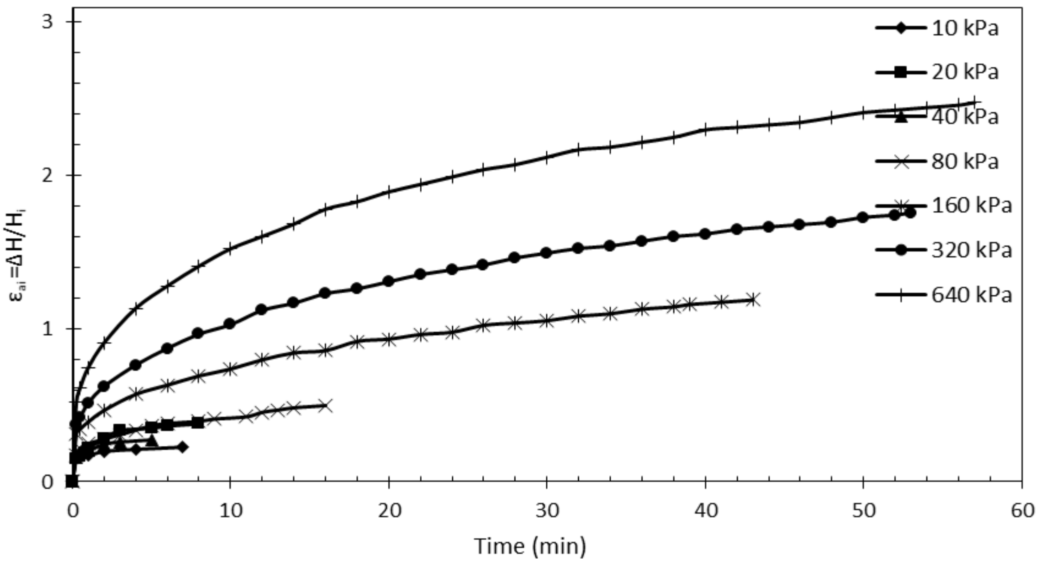

Figure 3.19: The variation of axial strain with time for immediate settlement (LP-2)

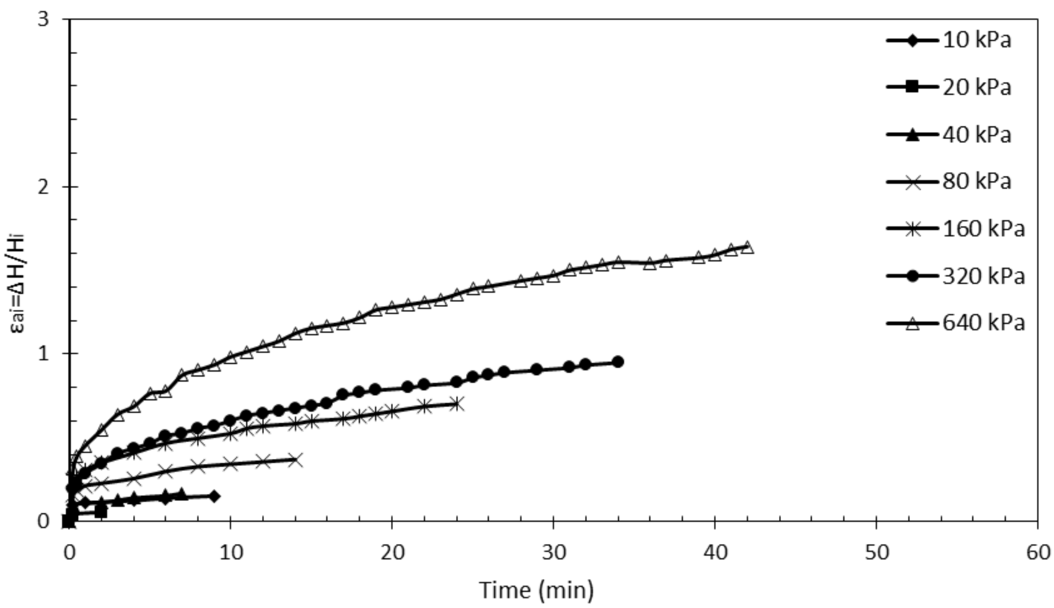

Figure 3.20: The variation of axial strain with time for immediate settlement (LP-3)

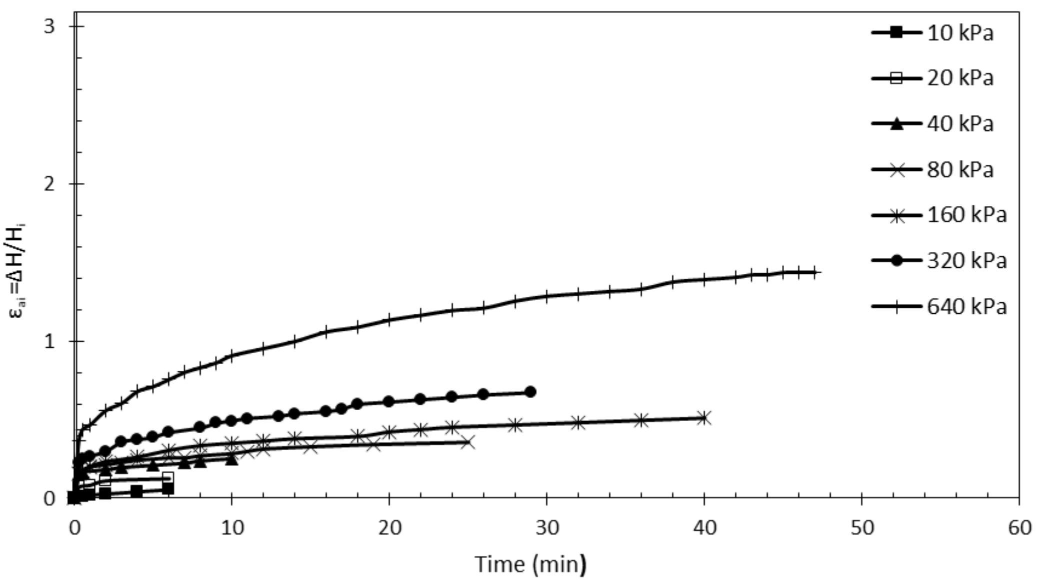

Figure 3.21: The variation of axial strain with time for immediate settlement (LP-4)

As it is advanced from lower to higher axial stress increases in the compression test, the undrained response of the specimens exceeded 20 minutes.

3.10.3 Results of Consolidation Stage

The consolidation settlement behavior is observed after completion of the undrained response by allowing for drainage of pore water. In this stage, the test is similar to the standard oedometer test. The axial displacements are recorded for 24 hrs and the pore water pressure measurements are carried out at the beginning and at the end of this period to check that the excess pore water pressure dissipation is completed. The results from the consolidation stage are presented in Figure 3.22 to Figure 3.25.

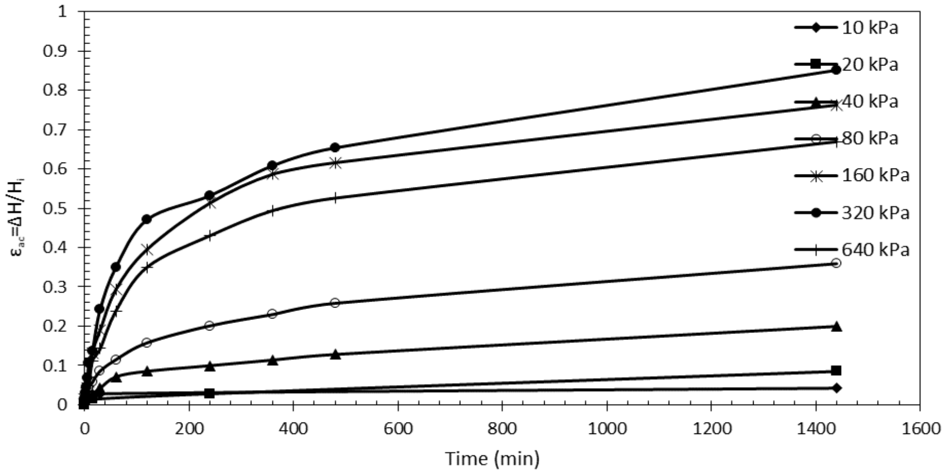

Figure 3.22: The variation of axial strain with time for consolidation settlement (LP-1).

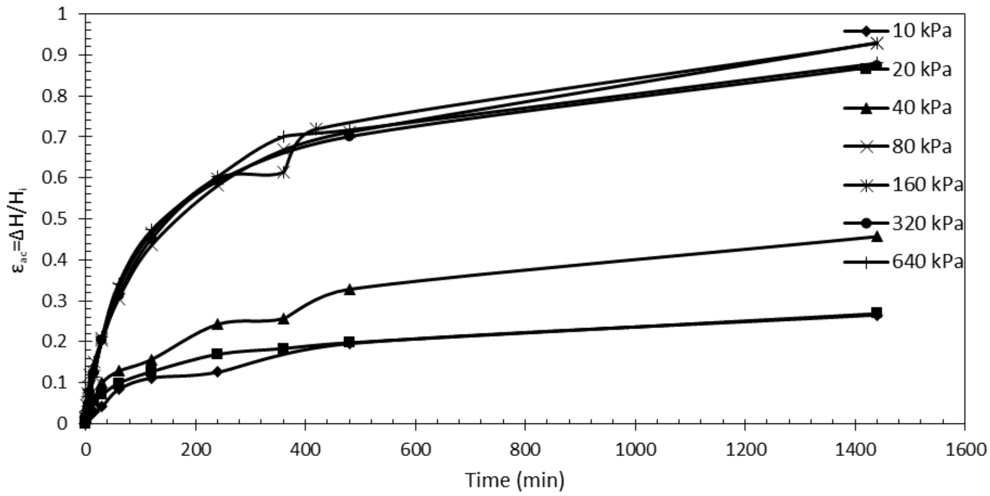

Figure 3.23: The variation of axial strain with time for consolidation settlement (LP-2).

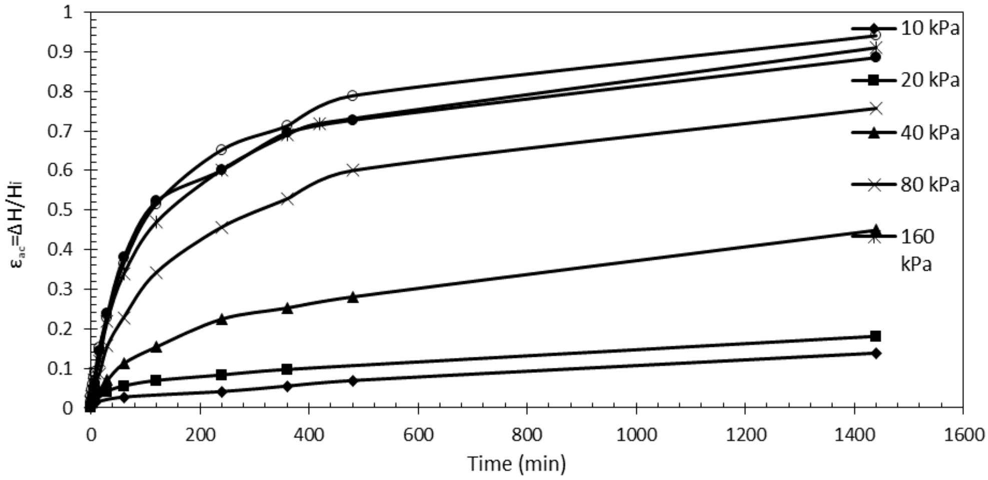

Figure 3.24: The variation of axial strain with time for consolidation settlement (LP-3).

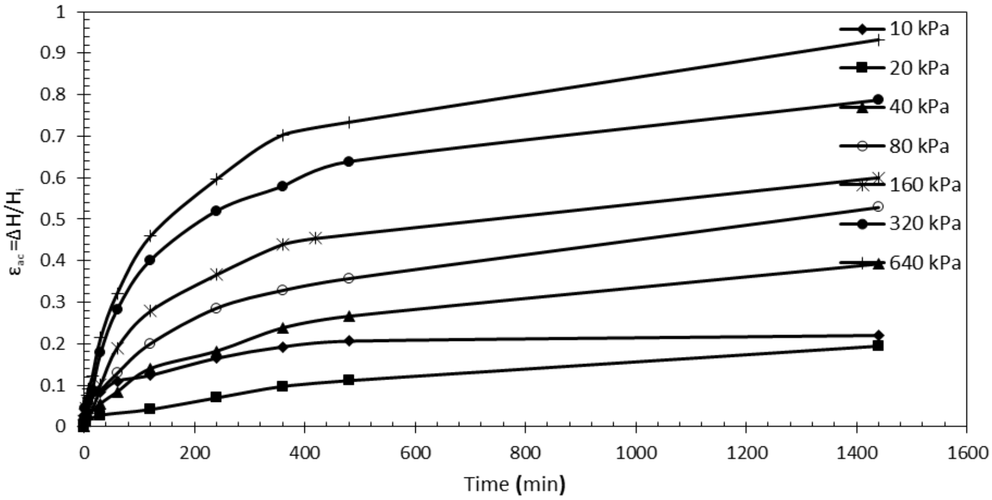

Figure 3.25: The variation of axial strain with time for consolidation settlement (LP-4).

3.10.4 The Variation of Axial Strain with Vertical Stress in Immediate Settlement

In this research the samples are subjected to the vertical stress in 7 stages of loading. Figure 3.26 shows the variation of axial strain versus vertical stress for different loading path.

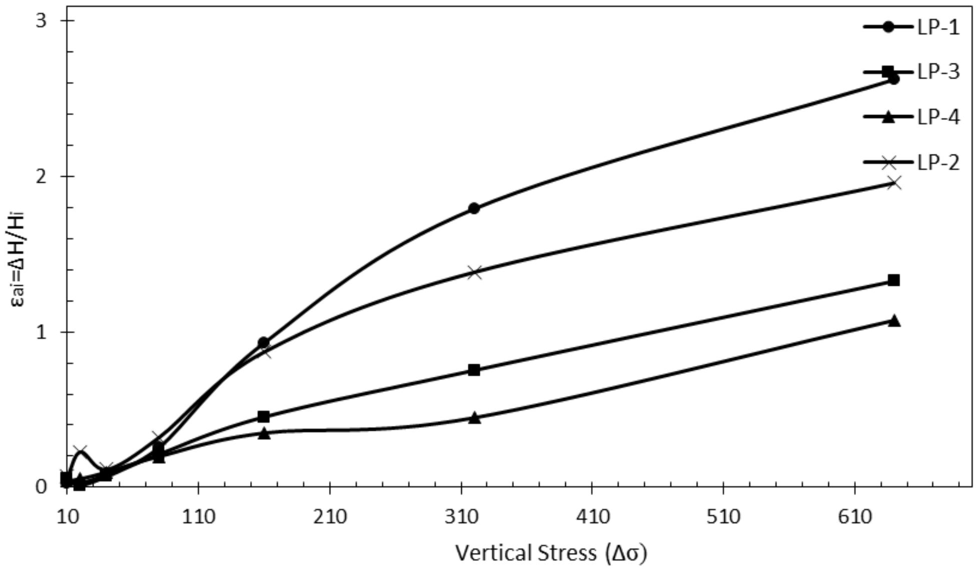

Figure 3.26: The variation of axial strain versus vertical stress for different loading paths.

3.10.5 The Variation of Axial Strain with Vertical Stress in the Consolidation Stage

The variation of axial strain versus vertical stress in long term settlement obtained from the modified device is observed. Moreover, this variation is compared to the result of axial strain obtained from the Standard Oedometer Test.

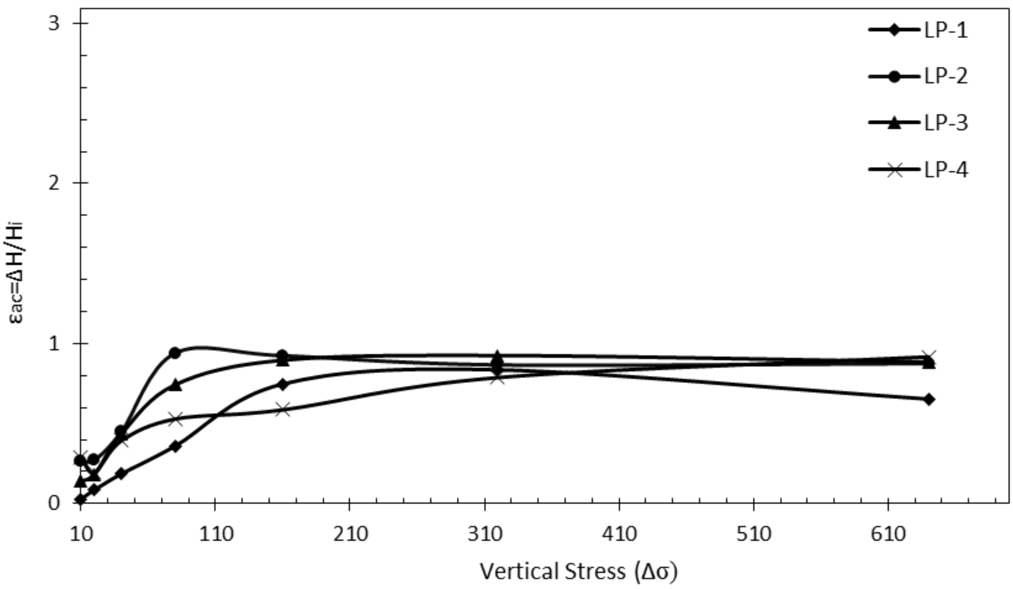

Figure 3.27: The variation of axial strain versus vertical stress for different loading paths and standard oedometer test

3.11 Results of the Controlled Rate of Strain Tests

The results of the CRS tests are presented in Figure 3.28, which also include the average results obtained from standard oedometer tests for comparison. It is observed that the load response obtained in the CRS tests are considerably stiff in the mid-range effective stress levels compared to the stress controlled oedometer tests.

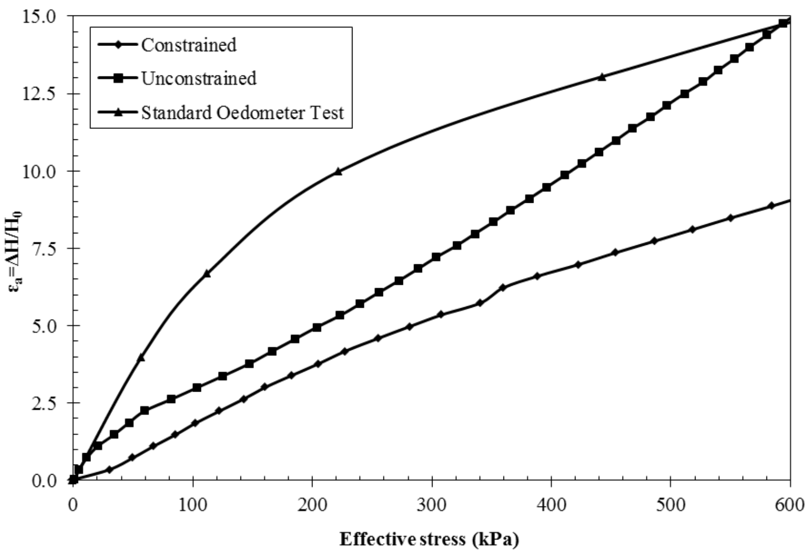

Figure 3.28: Results of CRS tests, comparison with standard oedometer test results.

Chapter 4

ANALYSIS AND DISCUSSION OF RESULTS

4.1 Introduction

In this chapter, analysis and discussion of the experimental results are presented. The main focus of the analysis and discussion will be on;

- the investigation of the immediate settlement behavior,
- assessment of the relationship between the immediate settlement, consolidation settlement and the total settlement.

4.2 Swell and Compressibility Behavior by Oedometer Test

One dimensional swell test results are presented as plots of percent swell versus logarithm of time in Chapter 3. The primary swell is evaluated from the curves and reported in Table 4.1 together with the compressibility characteristics.

The comparison of the primary swell results from the standard oedometer tests and the modified oedometer tests showed that there is a significant difference in the primary swell results between the two methods of testing. As discussed earlier in Chapter 3 this is considered to be mainly due to the difference in the mode of strain. In the standard oedometer tests, the sample is constrained, hence it is forced to swell in the vertical direction only, whereas in the modified tests the samples are allowed to swell in all directions within a flexible membrane. It is also observed from the results of the modified tests that the percent swell occurred in a variable manner in all samples. Hence the variation within the results of the modified tests only was also significant. It should also be noted that the method of saturation can be a major factor in the swelling behavior such that; in the standard oedometer test the samples were directly soaked in water in the consolidation cell allowing for a quicker and better saturation which was indicated in the swell measurements.

Table: 4.1: Compressibility characteristics of the soil specimen.

Parameter	Measured value
Compression index, C_c	0.239
Swelling index, C_s	0.118
Coefficient of consolidation, C_v (m^2/year)	0.250
Time required for 90% consolidation, t_{90}(min)	40
Hydraulic conductivity, k (m/s)	3.1×10^{-9}
Induced Preconsolidation pressure, σ_p', (kPa)	160
Swell pressure (kPa)	200

An assessment on the compressibility parameters of the soil specimens based on Kulhawy and Mayne (1990) indicates that, even though compacted specimens were used in this study, the parameters obtained in the test results are still within a range of ±50% of the predictions based solely on plasticity index suggested by these authors.

The coefficient of consolidation as obtained by following Taylor (1948) method, indicated that the rate of settlement of the soil specimens in the tests was very low. As expected to be observed for compacted cohesive soils, hydraulic conductivity, which is indirectly obtained using coefficient of consolidation, indicated a practically impermeably soil.

The induced preconsolidation pressure in the soil specimen is estimated following the methodology by Cassagrande (1936).

4.3 The interpretation of results obtained from the Controlled Rate of Strain Tests

The stiff response obtained in the CRS tests could be due to the strain rate adopted in the tests and, in the case of the unconstrained tests, the mode of strain. The other possibility for the difference observed could be due to the initial condition of the samples. The CRS tests are carried out for samples as optimum water content and maximum dry density, whereas the standard oedometer tests were carried out after initial saturation and at nearly fully saturated state.

4.4 Compressibility Behavior in Modified Oedometer Tests

The immediate settlement measurements are compared with the total settlement measured in the modified oedometer tests by calculating the axial strain. It is observed that as the ratio of the confining stress against the axial stress increases the contribution of immediate settlement to total settlement reduces.

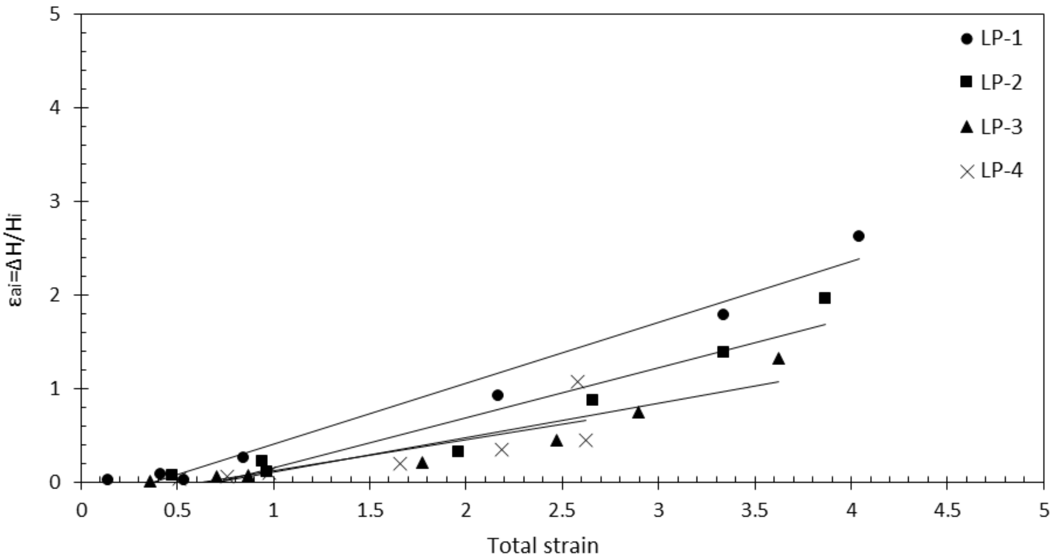

Figure 4.1: The variation of immediate settlement versus total settlement for each Loading Path.

As it is presented in Figure 4.1, LP-1 has the highest slope and the slope of LP-2, LP-3 and LP-4 reduces in the same order. The slope of LP-1, LP-2, LP-3 and LP-4 are 32.72 %, 27.48%, 16.11% and 16.02% respectively. It is also interesting to note that a two fold increase in the confining stress axial stress ratio causes halving of the slope of the immediate settlement versus total settlement curve measured in the modified oedometer test. It can be stated that, as the confining stress increases, due to an improved lateral support, there is less tendency in the specimens to displace laterally during axial stress increase.

The variation of immediate settlement in modified device versus long term settlement obtained from standard oedometer tests is presented in Figure 4.2. In this figure, the strain of each stage of loading in the modified device versus the same stage of loading in the standard oedometer test is plotted. As can be seen, the highest slope belongs to the LP-1 and LP-2, LP-3 and LP-4 reduce in order as the confining stress increase. The slope of LP-1 is 21.39 %, LP-2 is 19.85 %, LP-3 is 10.95 % and LP-4 is 8.94 %.

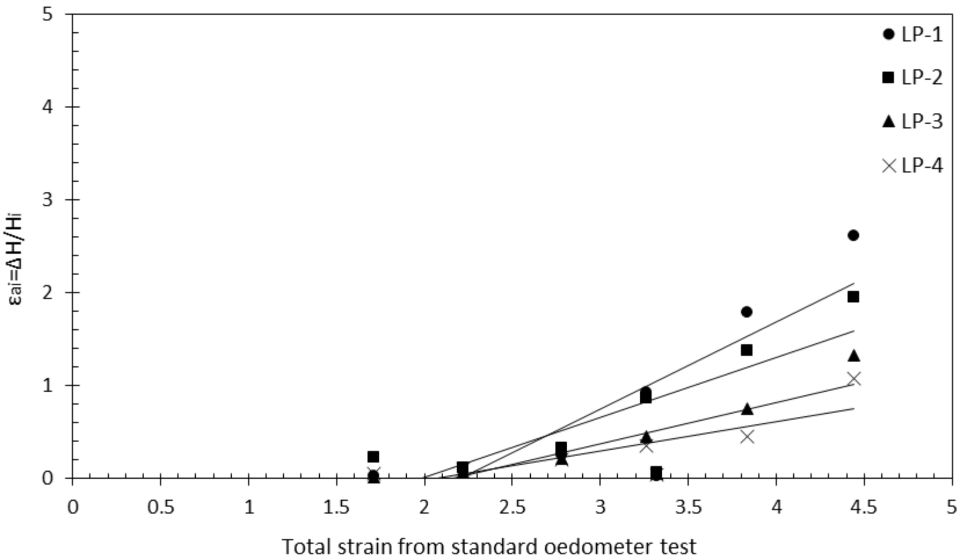

Figure 4.2: The variation of immediate settlement from modified device versus consolidation settlement obtained from standard oedometer test.

The above figure shows that, depending on the loading path, during consolidation stage there is an additional lateral displacement attained in the soil specimens compared to the fully restrained standard oedometer samples. The percentage of the additional axial strain due to lateral displacement is estimated to be approximately 30% of the total axial strain.

4.5 The Effect of Loading Path on The Compressibility Behaviour

In order to show the effect of the loading path on the relationship between immediate settlement and consolidation settlement, the ratio of the strains calculated for these two stages of the total compression measured in the modified test and the standard oedometer tests is plotted with respect to the loading path.

As it is presented in Figure 4.3, the proportion of immediate settlement and long term settlement obtained from the modified device is higher than the same proportion obtained from standard oedometer test, which confirms the previous discussion on the effect of confining stress on the lateral displacements during consolidation. According to the data shown on Figure 4.3, the slope of the immediate settlement and consolidation settlement ratio with respect to confining stress and axial stress ratio is such that, the contribution of immediate settlement to total settlement reduces by three fold against an increase of three fold in the latter.

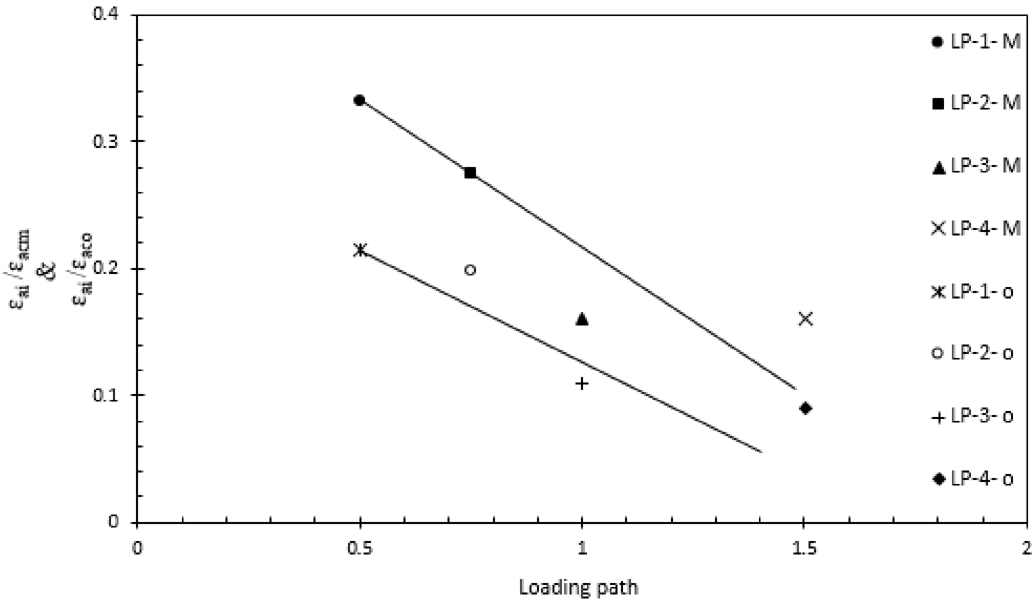

Figure 4.3: The variability of proportion of immediate settlement with long term settlement obtained from modified device and long term settlement from standard oedometer test.

The assessment carried out on the ratio of immediate settlement and consolidation settlement reveals that there is two fold decrease. Hence, it is shown with the above data that there is a strong relationship between the proportion of immediate settlement and total settlement and consolidation settlement and both relationships are significantly influenced by the confining stress.

Chapter 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusions

The subject dealt with in this research is experimental work. Investigation of relationship between distortion settlement, lateral spreading and consolidation settlement of selected cohesive soil is the topic of this study. In this empirical work, the immediate settlement behavior is observed to occur in a period time between 10 to 15 minutes but this behavior of soil exceeded this time period as axial load increases. The sample is left for one day of consolidation and then measuring the immediate settlement and consolidation settlement are started. Nevertheless, it is hoped that the results obtained in this study could be in the same range of results achieved by Burland (1977).

For this reason a few of the most significant outcomes of the research done by Burland (1977) are listed as follows:

- For Normally Consolidated Clay (with $\sigma_o' + \Delta\sigma' > \sigma_p'$); the proportion between immediate settlement and consolidation settlement (S_i/S_c) is 0.1
- For over Consolidated Clay (with $\sigma_o' + \Delta\sigma' < \sigma_p'$); this ratio ($S_i/S_c$) is located in the range between 0.5-0.6.
- For deep strata of over consolidated clay this proportion shows up to 0.7.
- And for non- homogenous and anisotropic soil is 0.25.

In this study the normally consolidated clay is investigated to specify the relationship between immediate settlement and consolidation settlement behavior.

The results obtained in this study are as follows:

- The variation of immediate settlement from modified device versus consolidation settlement for different loading paths demonstrate that the proportion of S_i/S_c for LP-1 is 0.32 and as the confining stress enhances this ratio (S_i/S_c) reduces in order so that it is dropped to 0.27, 0.161 and 0.160 for LP-2, LP-3 and LP-4 respectively.

Furthermore,

- The variation of immediate settlement behavior versus consolidation settlement obtained in the standard oedometer show that the ratio of immediate settlement and consolidation settlement (S_i/S_c) shows 0.21 for LP-1 and as the confining stress increases this ratio starts to have a descending trend, 0.19, 0.10 to 0.08 for LP-2, LP-3 and LP-4 respectively.

Moreover,

It is observed that the obtained ratio between immediate settlement and consolidation settlement is greater than those obtained from standard oedometer which approves the impact of confining stress on lateral spreading during consolidation.

5.2 Recommendation

- Literature survey shows that, a few studies have been conducted on the relationship between immediate settlement and consolidation settlement. More studies regarding this investigation need to be considered.
- One of the most important characteristics regarding immediate settlement behavior is considering the lateral spreading which needs to be investigated in further researches.
- In this study a small shape of sample is considered, so the effect of shape size, on immediate settlement should be investigated.
- Investigating different types of soil is important, so considering the immediate settlement for various soil types and different water contents need to be done.
- Measurement of excess pore water pressure should be studied.

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