

**ADDIS ABABA UNIVERSITY**  
**ADDIS ABABA INSTITUTE OF TECHNOLOGY**  
**SCHOOL OF CIVIL AND ENVIRONMENTAL**  
**ENGINEERING**



**A Study of Dynamic Properties of Soils Found in  
Yeka subcity Area of Addis Ababa**

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A thesis submitted to the school of Graduate Studies of Addis Ababa  
University in partial fulfillment of the requirement for the Degree of  
Master of science in Geotechnical Engineering

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## **DECLARATION**

I hereby declare that this thesis is my original work that has been carried out under the supervision of prof. Alemayehu Teferra. Furthermore, this work has not been submitted to any other University or Institution for the award of any degree or diploma and all sources of materials used for the thesis have been duly acknowledged

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## LIST OF SYMBOLS AND ABBREVIATION

<b>Symbols</b>	<b>Description</b>
AAIT	Addis Ababa institute of Technology
a	Parameter that depends on plasticity of the soils
A loop	Area of a loop
ASTM	American society for testing materials
D	Damping ratio
ES EN -8	Ethiopian standards based on euro norms
e	Void ratio
G	Shear modulus
G <sub>s</sub>	Specific gravity
G <sub>max</sub>	Initial (maximum) shear modulus
NGI	Norwegian Geotechnical Institute
LL	Liquid limit
PL	Plastic limit
PI	Plasticity index
OCR	Overconsolidation ratio
TP	Test pit
UCS	Unified Soil Classification system
V <sub>s</sub>	Shear wave velocity
$\sigma'_m$	Mean principal stress
$\rho$	Density of soil
$\tau$	Shear stress
$\gamma$	Shear strain

## ABSTRACT

Yeka sub-city is located in the North East part of Addis Ababa. The geographical location of Yeka subcity is  $9^{\circ}12'$  latitude N and  $38^{\circ}50'$  E longitude. The subcity is characterized by variable topographic features. Addis Ababa is located in seismic zone 3 according to ES EN 2015. The city has moderate seismicity. However, if damage occurs due to moderated seismic activity, its effect might be significant compared to an earthquake occurring on remote areas. Yeka subcity is one of the highly populated areas of Addis Ababa. To reduce future seismic damages, it's necessary to determine the response of soil deposits in the subcity .Hence the objective of this research is to investigate the dynamic properties of soils found in Yeka subcity.

The index properties investigated in this study include; particle size analysis, atterberg limits, free swell and specific gravity. The result of the study showed that, liquid limit ranges from 53 to 85 %, plasticity index ranges between 23 to 45 %, specific gravity values are between 2.61 to 2.71 and free swell ranges 59 to 128 %.

According to Unified Soil Classification System, common soils found in Yeka subcity are classified as elastic silt and plastic clay. In this paper, the shear modulus and damping ratio values of soils commonly found in Yeka subcity was determined using cyclic simple shear test machine on undisturbed samples. The tests were conducted as a function of strain amplitude of 0.01 %, 0.1 %, 1 %, 2.5 % and 5 % under axial stress of 100 kPa, 200 kPa, and 400 kPa.

The normalized shear modulus values were determined and the results were compared with curves developed by (Seed and Idriss 1970; Vucetic and Dobry 1991; Dimer 2013; Gemechu 2011; Mengistu 2014).The results reveal that the normalized shear modulus values at lower strains ( $< 0.01$  %) are lower than published literature data. This reduction in values could be due to sample preparation and testing condition. However for higher strains, the computed shear modulus values are within the limits indicated in published literature data.

Comparisons were also made with local soils. The shear moduli of the studied soils are fitted well with curves developed for clay soils of Arbaminch and very close to silty soils of Adama. However, the values show slight scatter with silty soils of Ziway.

The determined damping ratio values for confining stress of 100 and 200 kPa are within the curve provided by Seed and Idriss (1970) for saturated clays. However, for confining stress of 400 kPa the values are outside the limits.

## CHAPTER ONE

### 1 Introduction

#### 1.1 Background

Earthquakes cause catastrophic damages to civil engineering structures like highways, dams, embankments, ports, bridges, and buildings. Earthquake also triggers secondary disasters like landslides, lateral spreading and liquefaction. To reduce damage of such structures and loss of life, geotechnical engineers have to deal with the effects of earthquake during design and construction.

It is very important to assess the possibility of soil failure during seismic events particularly in sites that are within earthquake prone region, consisting problematic soils (loose sand, sensitive clays), heavily populated areas and sensitive structures like nuclear plant. The proximity of significant earthquake activities near major population centers such as Addis Ababa, obviously leads to the question of how much damage will be sustained by the structures. Hence, it is essential to know the ground response of soil deposits in addition to the requirement of strict structural earthquake design guidelines. In order to study problems involving soil -structure interactions, site responses of soil deposits, and prediction of the ground motion, it is essential to know the critical dynamic properties of natural soil deposits.

Two of the most important parameters required for dynamic analysis are the soil stiffness (Shear modulus) and material damping (Damping ratio). These soil properties are used to assess the dynamic response of soils at different strain levels.

Dynamic soil responses are needed for earthquake analysis, in machine foundation design, nuclear power plant foundations, fast transportation systems, blast resistant structures, the response of offshore soils and supported structures to ocean wave loads.

The distribution and nature of earthquake damage is strongly affected by response of local soil deposits and earth structures under seismic loading conditions. Researches had been conducted in Dessie town, Ziway town, Adama town, Arbaminch town and Gulelle area of Addis Ababa.

In this study, the dynamic soil properties of Yeka subcity are determined to create awareness and to provide dynamic soil information for future designs.

There are different laboratory and field test methods available to determine the dynamic properties of the soil, but each technique has its problem and limitation. Laboratory tests generally provide the most direct means of evaluating dynamic soil parameters for seismic analyses. The laboratory tests are classified into three groups. These are of small strain, medium strain and large strain range depending on the amplitude of the lateral dynamic load exerted. Even though laboratory tests are available at broad strain ranges, they are greatly influenced by sample disturbance. Some of the laboratory tests available to measure the dynamic properties of soils at different strain levels include: -resonant Column test, travel time test, ultrasonic pulse test and the piezoelectric bender element test and cyclic simple shear test are the commonly employed techniques (Luna and Jadi 2000). For this study, the cyclic simple shear test is used.

Field Geophysical tests give reliable and precise output especially at low strain levels, since they determine the dynamic properties of soils at their natural in situ condition (kavazanjian et al. 1997). Geophysical tests are often based on the measurement of body wave velocities. The procedures of these tests therefore involve the creation of transient or steady-state elastic waves and the observation of these waves at one or several locations. Several sources can be used to generate the waves: sledge hammers, mechanic hammers, explosions, drop weights etc. These sources create dilatational, shear and surface waves.

Geophysical tests generate seismic waves into soil formations at a very low strain level. This low level of strain allows the use of elastic theory to associate measurements with mechanical properties, and for the most part, the response is linear. Some of the geophysical tests include;

- Seismic refraction test
- Seismic reflection test
- Down hole test
- Cross hole test

Geophysical tests give reliable results for low strain levels. These geophysical tests have the advantage that the state of the stress is inherently included in the procedure. Furthermore, they test undisturbed soil in the actual field conditions with the actual effective stress and drainage conditions.

## **1.2 Objective of the study**

General objective

The principal objective of this research is to investigate the dynamic soil properties, namely shear modulus and damping ratio, of soils found in Yeka subcity Area.

Specific Objectives

- Study the factors that influence the dynamic properties of soils of Yeka subcity.
- Comparison of normalized modulus reduction and damping potential values of the soils with literatures so as to determine whether results show agreement with previous trends.

## **1.3 Methodology**

To meet the objectives of the research program;

- Undisturbed and disturbed soil samples had been collected from 2.50 m depth, from 8 representative test pits.
- In situ field density has been determined using core- cutter method.
- In laboratory, undisturbed samples had been used for cyclic simple shear test and one dimensional consolidation test. Disturbed samples have been used to determine grain size analysis, atterberg limits and to classify soils.
- Shear modulus and damping ratio values of soils have been computed.
- Comparison of results with literatures data is undertaken.

#### **1.4 Scope of the study**

The scope of the study is limited to investigation of the dynamic properties (i.e. shear modulus and damping ratio) of the soils of the Yeka Area using the cyclic simple shear test.

#### **1.5 Organization of the thesis**

Chapter one gives general introduction, including background, objectives, methodology and scope of the study. Literature review is presented in Chapter two regarding previous works on dynamic properties of soils. Chapter three focuses on study area, data collection method, materials, and experimental techniques used in the study. Chapter four gives attention to summary of basic index properties of soils and cyclic shear test results. Chapter five deals with comparison of results with previously published literature data. Chapter six presents conclusions and recommendations.

## CHAPTER TWO

### 2 Literature Review

#### 2.1 Introduction

There are a number of natural and man-made phenomena which produce dynamic fast (monotonic) and cyclic (repetitive) loading environments affecting civil engineering structures (kavazanjian et al. 1997). They include earthquakes, machine vibrations, pile driving, explosions, and ocean wave storms. To evaluate the effect of such loads, it is necessary to understand and measure the dynamic and cyclic properties of soils involved.

Geotechnical materials, from soil to rock, influence the damage earthquakes cause in two primary ways: (1) by modifying the manner in which the ground shakes at a particular site and (2) through the process of ground failure in which a mass of soil experiences permanent deformations (e.g. settlement or landslide). Both can cause significant damage to, and even the destruction of, structures and constructed facilities, and must be considered in seismic hazard evaluation and earthquake resistant design (Kramer 1996).

Ground motion under earthquake loading is influenced by the dynamic properties of soils. The values of dynamic properties of soils mainly shear modulus and damping ratio are influenced by plasticity index, void ratio, relative density, number of cycles, grain size distribution, type of soils, over burden pressure, location of ground water and amplitude of earthquake (amplitude of cyclic loading). The shear modulus and damping ratio are obtained from laboratory and field tests.

## **2.2 Basic mechanical properties of soils**

Both site response and ground failure are strongly influenced by properties of soils. Site response is primarily influenced by the properties that control wave propagation, particularly stiffness and damping. Ground failure is influenced by those properties, but also by the shear strength of the soil (Vucetic and Dobry 1987). The dynamic analysis of soil properties uses the same parameters that are used in the analysis of static behavior of the soils. These parameters are used in the analyses of many types of foundations and earth structures like embankment dams. These soil properties include specific gravity, plasticity index, and grain size distribution.

## **2.3 Cyclic loading and load response**

The concept of dynamic loading of soil refers to the propagation of stress waves through soil layers. The term “Cyclic” refers to systems oscillating with constant amplitude and frequency. Cyclic loadings are loads that exhibit a degree of regularity both in their magnitude and frequency. One of the most recognizable forms of a soil in a cyclic loading scenario happens during an earthquake and machine vibration-induced loading on foundations.

Dynamic loading is influenced by the response of soil deposits and the soil response in turn is governed by the dynamic soil properties. Soils’ responses subjected to dynamic and cyclic loading are strongly controlled by mechanical properties of the soil, which basically includes shear modulus (shear wave velocity), damping, Poisson's ratio and density. Of these, shear modulus and damping are the most pertinent material properties with which to characterize the dynamic behavior of soils. Soil response analysis is used to evaluate dynamic stress and strains that lead to instability of earth structures.

Appropriate evaluation of shear modulus and damping characteristics of soils subjected to dynamic loadings is the basic element to accurate seismic response analysis. A typical soil subjected to cyclic loading exhibits nonlinear and hysteresis response, which is the result of stress-strain curve.

The behavior of soil under cyclic loading is non-linear and depends on some factors including soil type, confining pressure, plasticity, number of loading cycles, and amplitude of loading. Parameters describing the cyclic soil properties required for a dynamic analysis include: damping ratio, the initial shear modulus at small shear strain ( $G_{max}$ ) and the modulus reduction and damping curves for the soils (Ishihara 1996).

### **2.3.1 Shear modulus and damping ratio**

The shear modulus and damping ratio of cyclically loaded soils are critical to the evaluation of many geotechnical earthquake engineering problem for low, intermediate and high strain amplitudes. Soils are elasto- plastic material which exhibit linear and non-linear behavior depending on the strain amplitude. Soils behave linearly on very small strain levels (<0.001 %) and responds non linearly at intermediate (0.001 % -0.01 %) and high strain amplitudes (>0.01 %)

Shear modulus is a parameter used to show the resistance of a material due to applied dynamic loading. Shear modulus is usually expressed as the secant modulus,  $G$  determined by the extreme points on the hysteresis loop (Seed and Idriss 1970). Its value relies on the amplitude of strain for which hysteresis loop is determined and it must be determined as functions of the induced strain in a soil specimen or soil deposit.

This hysteresis loop is obtained from stress-strain values which are the results of laboratory test such as tri-axial and cyclic direct simple shear test. Figure 2.1 below, shows the relationship between stress- strain loop for a cycle of loading and material damping.

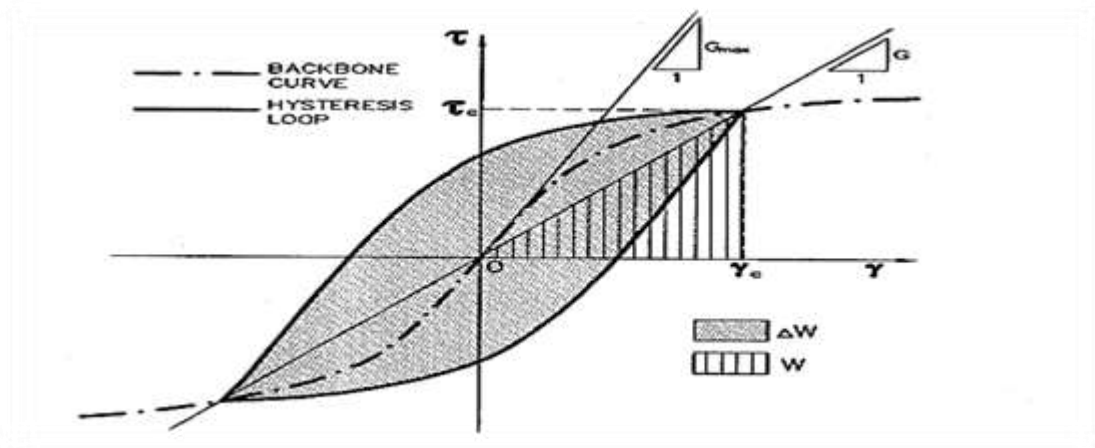


Figure 2.1: Hysteretic stress-strain response of soil subjected to cyclic loading  
(kavazanjian et al. 1997)

The Damping ratio can be determined from the following formula which is based on stress- strain hysteresis loop shown above in Figure 2.1.

$$D = \frac{\Delta W}{4\pi W} \quad (2.1)$$

Where

W- The maximum stored energy

$\Delta W$  - The energy lost per cycle inside the hysteresis loop

D - Damping ratio

The Secant shear modulus represents the average shear modulus and obtained by connecting extreme points of the hysteresis loop. This approach is mostly employed and gives representative value of shear modulus. Damping ratio (material damping) is the inherent capacity of the soils to dissipate energy. Its value increases with increasing magnitude of cyclic shear strain. It is also proportional to the area inside the hysteresis loop. This hysteresis effect represents the dissipation of energy in the soil. Energy is dissipated through several mechanisms, such as heat, friction between solid particles in the skeleton and relative motion between the skeleton and the pore fluid.

Damping ratio has a very important effect on the consequences of the cyclic loading of soils. For instance, if a soil that had no damping were to be excited by an external momentary load that would cause it to vibrate, it would vibrate indefinitely and with unchanging amplitude. Soil damping allows such an excitation to decrease over time until it is no longer felt.

It is important to distinguish between material damping and radiation damping, the former being the dissipation of energy through internal soil friction, and the latter, the dissipation of energy from the natural spreading of energy/motion waves through space. Of these types of damping, only material damping is dependent on the soil's characteristics and not on the soil's overall geometry and boundaries.

Shear modulus and damping ratio occur in pairs. Plot of these two parameters is known as modulus reduction curve. As seen from the Figure 2.2 , the stiffness of soil decreases as the cyclic shear strain increases. However, damping ratio of soils increases with an increase in cyclic shear strain.

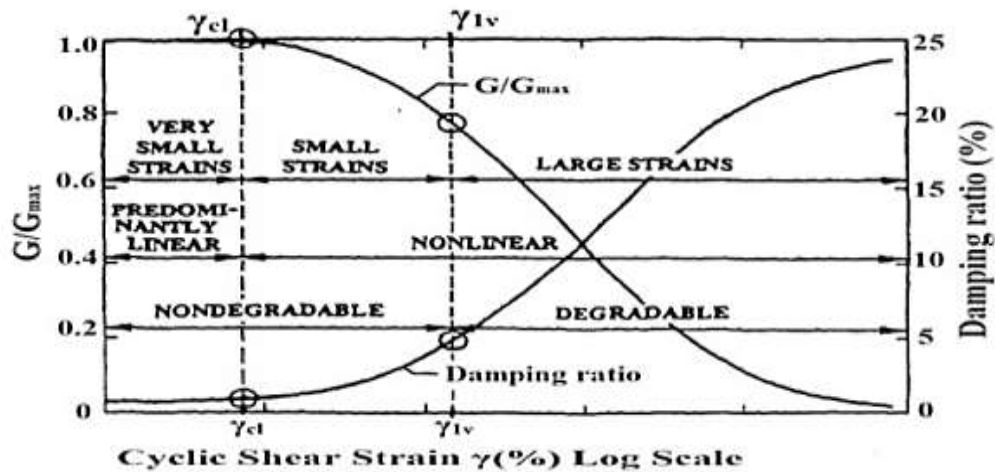


Figure 2.2: Normalized shear modulus reduction and damping ratio curve (Jia 2018)

By improving the engineering properties of soils such as by compaction, we can enhance the damping potential of soils. Research conducted on red clay soils of Gulelle Area have shown that the damping ratio of undisturbed soil samples is about 0.6 to 0.7 times the damping ratio of remolded soils (Bedada 2010). However, improving the engineering properties has adverse reduction effect on the shear modulus of soils.

### **2.3.2 Methods of determining Shear modulus and Damping ratio**

A wide variety of procedures, including laboratory and field tests have been used to estimate both shear modulus and damping characteristics. The main procedures are listed below (Seed and Idriss1970).

- a. Forced vibration tests
- b. Free vibration tests
- c. Direct determination of stress- strain relationships
- d. Field measurement of wave velocity

#### **a. Forced vibration tests**

Forced vibration tests, involving the determination of resonant frequencies and measurement of response at other frequencies have been used to determine both moduli and damping factors. Test conditions in the laboratory have included the application of longitudinal and torsional vibrations to cylindrical samples or shear vibrations to layers of soil placed on a shaking table. These procedures are useful for determining properties at relatively low to moderate strain levels (Seed and Idriss1970).

#### **b. Free vibration tests**

Free vibration tests, in which measurements are made of the decay in response of a soil sample or soil deposits, have been used to measure both moduli and damping factors for soils. Methods of excitation are similar to those used for forced vibrations tests, but the procedure can be used for measurement of soil characteristics at relatively low to moderately high strain levels (Seed and Idriss1970).

#### **c. Direct determination of stress- strain relationships**

Hysteretic stress- strain relationships can be determined in the laboratory by means of triaxial compressional tests, simple shear tests or torsional shear tests conducted under cyclic loading conditions. In general these procedures are useful for measuring moduli and damping factors under moderate to relatively high strains (Seed and Idriss1970).

**d. Field measurement of wave velocity**

In situ (field) tests have been used to measure the velocity of propagation of body waves (compressional waves, shear waves) and surface waves (Rayleigh waves) from which values of soil modulus can readily be determined for low strain conditions. However, these procedures have not provided values of damping factors (Seed and Idriss 1970).

Table 2.1: Test procedures for measuring shear moduli and damping ratio (Das 1993)

General Procedure	Test condition	Approximate Strain range ( $\gamma$ )	Properties that can be determined
Determination of Hysteresis stress-Strain relationships	Triaxial compression	$10^{-2}$ to 5 %	Modulus: Damping
	Simple shear	$10^{-2}$ to 5 %	Modulus: Damping
	Torsional shear	$10^{-2}$ to 5 %	Modulus: Damping
Forced vibration	Longitudinal vibrations	$10^{-4}$ to $10^{-2}$ %	Modulus: Damping
	Torsional vibrations	$10^{-4}$ to $10^{-2}$ %	Modulus: Damping
	Shear vibration-lab	$10^{-4}$ to $10^{-2}$ %	Modulus: Damping
	Shear vibration –field	$10^{-4}$ to $10^{-2}$ %	Modulus: Damping
Free vibration tests	Longitudinal vibrations	$10^{-3}$ to 1 %	Modulus: Damping
	Torsional vibrations	$10^{-3}$ to 1 %	Modulus: Damping
	Shear vibration-lab	$10^{-3}$ to 1 %	Modulus: Damping
	Shear vibration –field	$10^{-3}$ to 1 %	Modulus
Field wave velocity Measurements	Compressional waves	$5 * 10^{-4}$ %	Modulus
	Shear waves	$5 * 10^{-4}$ %	Modulus

**2.3.3 Dependency of deformation characteristics upon shear strains**

The deformation characteristic of soils varies to a larger extent depending upon the magnitude of shear strains to which the soil is subjected. The approximate range of shear strains induced produces elastic, elasto-plastic and failure states of stress.

In small strain regions ( $<10^{-5}$ ), the deformation characteristics exhibited by most soils is purely elastic and recoverable. The phenomena associated with such small strains would be vibration or wave propagation through soil grounds (Ishihara 1996).

The small strain shear modulus,  $\mu_0^s$  is presented in Figure 2.3 by the slope of the tangent to the stress-strain curve at a zero strain. It can be seen from the Figure 2.3 that, at small strain ranges, the material indeed behaves linearly as the stress-strain curve closely follows the tangent at zero strain. As a consequence, almost no hysteresis effect is present at these strain levels. At strain levels around  $10^{-5}$  soils typically exhibit a softening non linearity or a decrease in modulus as strain increases.

This degradation can be seen in Figure 2.3, as the decrease of the secant modulus with increasing strain. This shear modulus degradation also causes progressively larger hysteresis in the stress-strain relation, leading to strain dependent material damping.

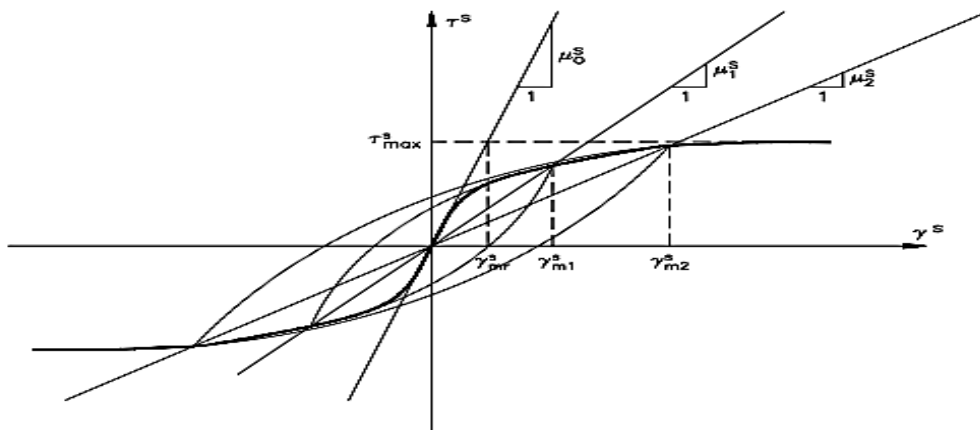


Figure 2.3: Typical stress –strain path for a soil under cyclic loading (Luna and Jadi 2000)

Over the intermediate range of strain ( $10^{-4} - 10^{-2}$ ) the behavior of soils is elasto- plastic and produces irrecoverable permanent deformations. The development of cracks or differential settlements in soil structures appears to be associated with the elasto-plastic attributes of the soils exhibited within such range of strain. When large strains ( $>10^{-2}$ ) are imposed on soils, the strains tend to become considerably large without a further increase in shear stress and failure takes place in the soils. Slides in slope or compaction and liquefaction of cohesion less soils are associated with failure inducing large strains.



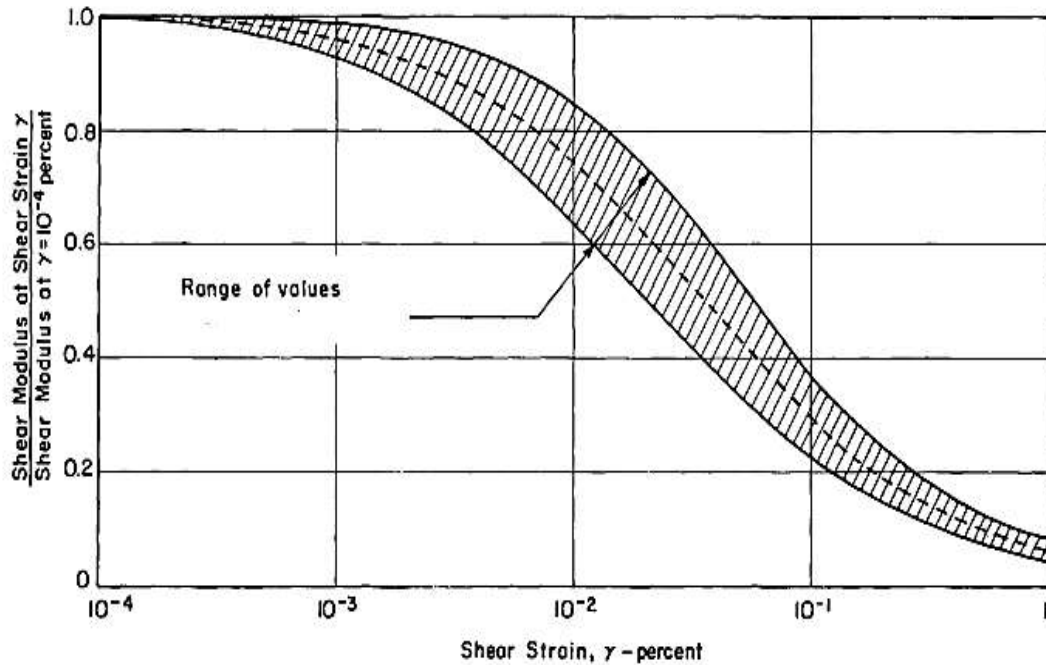


Figure 2.4: Variation of shear modulus with shear strain for sands (Seed and Idriss 1970)

### 2.4.2 Number of cycles

For a given value of mean effective stress and shear strain the shear modulus slightly increases and damping ratio decreases with the number of cycles. For most seismic events, the number of significant cycles is likely less than 20. The value determined at 5 cycles provides reasonable values for all practical purposes (Das 1993). Furthermore, the effect of number of cycles practically disappears when stress application is repeated for more than 10 cycles.

### 2.4.3 Plasticity index

Unlike other factors plasticity index dominantly and consistently affects the shear modulus value of cohesive soils (Seed et al. 1988). (Vucetic and Dobry 1991) reported that, with an increase in PI, soils are more resistant to cyclic loading and modulus reduction takes places in a slower rate. As seen from Figure 2.5 below, highly plastic soils exhibit more linear response than non-plastic soils.

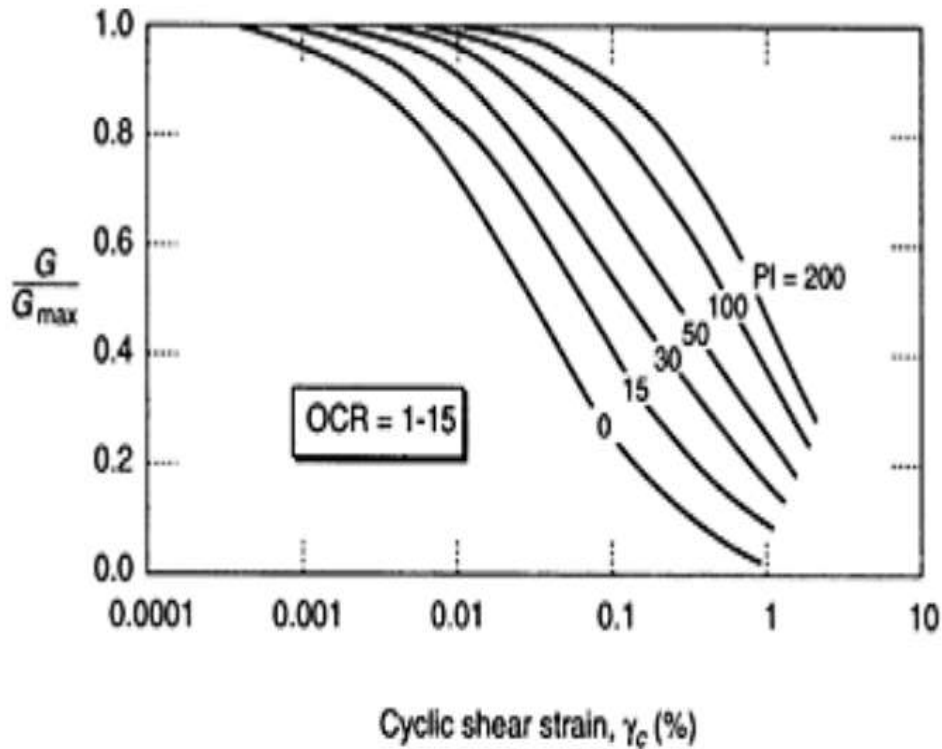


Figure 2.5: Relation between  $G/G_{max}$  and strain curves and soil plasticity for normally and over consolidated soils. (After Vucetic 1991 as referred by Kvazanjan et al. 1997)

#### 2.4.4 Confining pressure

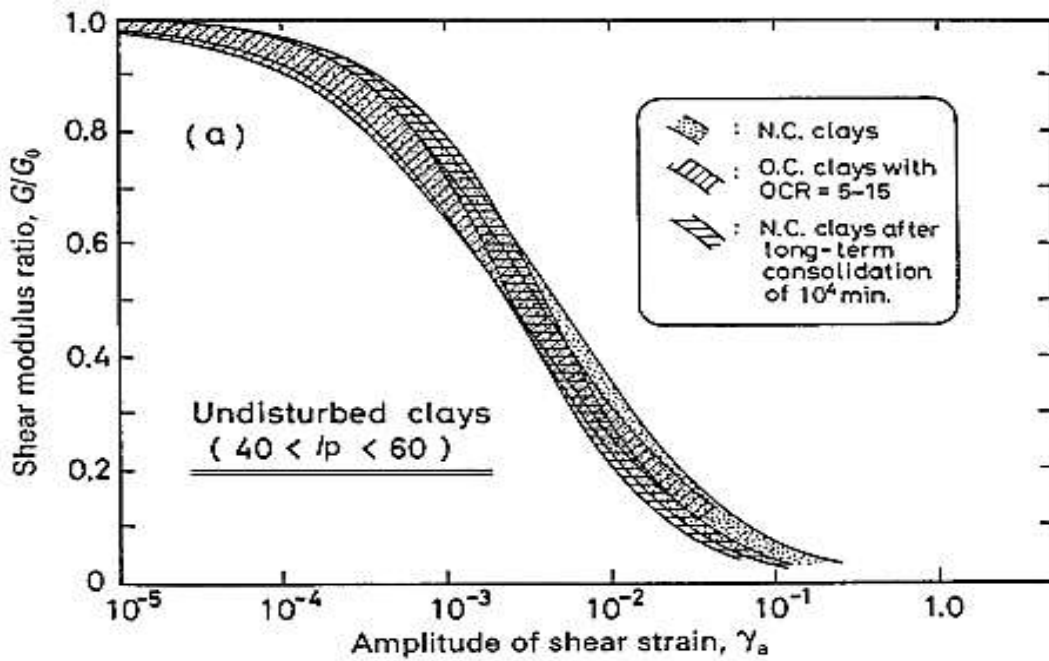
With an increase of confinement, the shear modulus of soil increases and damping ratio decreases. This effect is predominately visible in case of cohesion less soils. However, confining pressure does not show significant effect on normalized shear modulus values of cohesive soils. Various researchers concluded that the effect of confining pressure on the normalized shear modulus gradually diminishes as the plasticity of the soil increases (Seed et al. 1988).

Table 2.3: Influence of confining pressure and change in normalized modulus reduction on clays (Seed et al. 1988)

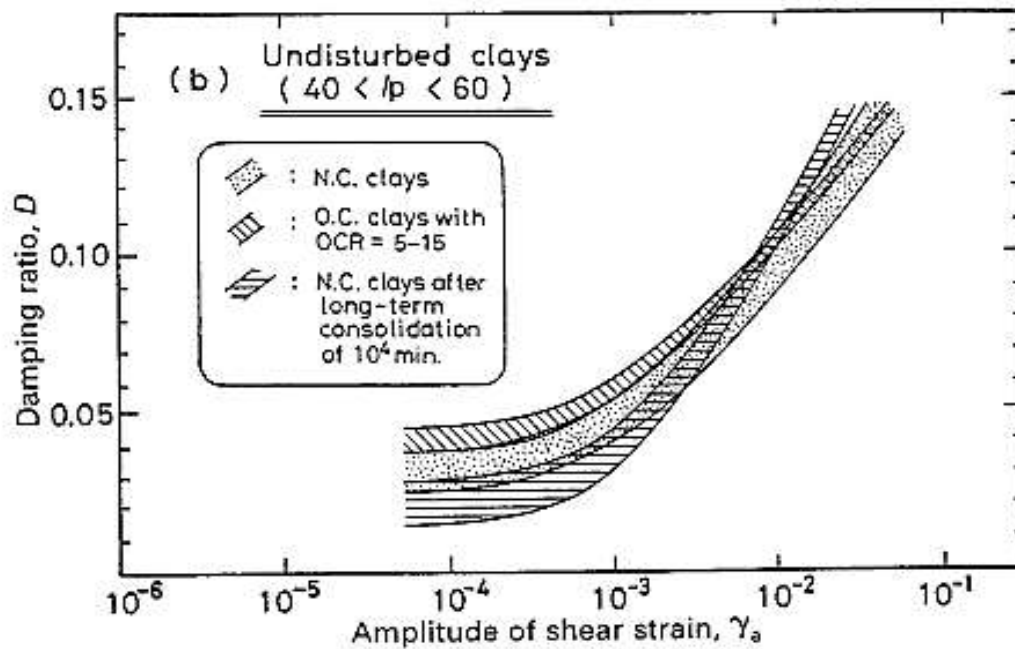
PI	Confining pressure change	Change in $G/G_{max}$	Reference
N.P	10 to 80 psi	$\approx 20\%$	(Stoke and Lodde 1978)
N.P	1 to 3 ksc	$\approx 16\%$	(Zen et al. 1978)
25	50 to 400 kPa	$\approx 7\%$	(Kim and Novak 1981)
25	1 to 3 ksc	$\approx 5\%$	(Zen et al. 1978)
35	1 to 3 ksc	$\approx 0\%$	(Zen et al. 1978)
35	10 to 80 psi	$\approx 10\%$	(Stoke et al. 1980)
30 – 40	-	$\approx 0\%$	(Andreasson 1981)
38 - 56	7 to 70 psi	$\approx 0\%$	(Kokusho et al. 1982)
40	15 to 60 psi	$\approx 0\%$	(Isenhower and Stoke 1981)

#### 2.4.5 Consolidation history

(Seed et al. 1988) summarized the effect of consolidation histories for undisturbed natural clay soils having medium to high plasticity index. As seen from Figure 2.6 , the shear modulus and damping ratio values are within narrow strand and do decrease or increase with the same proportion over a wide range of strain. Hence, neither shear modulus nor damping is significantly influenced whether a soil is normally consolidated or over consolidated.



(a)



(b)

Figure 2.6: Influence of consolidation history on strain dependent (a) shear modulus and (b) damping ratio (After Kokusho et al. 1982 as referred by Seed et al .1988)

### 2.4.6 Void ratio

Void ratio is an important factor influencing shear moduli and damping ratio of sands. As studied by (Hardin and Drenvich 1972), the shear modulus increases and damping ratio values decrease with a reduction in void ratio as shown Figure 2.7. However, as seen from Figure 2.8, the effect of void ratio on shear modulus values wears off at high strain values.

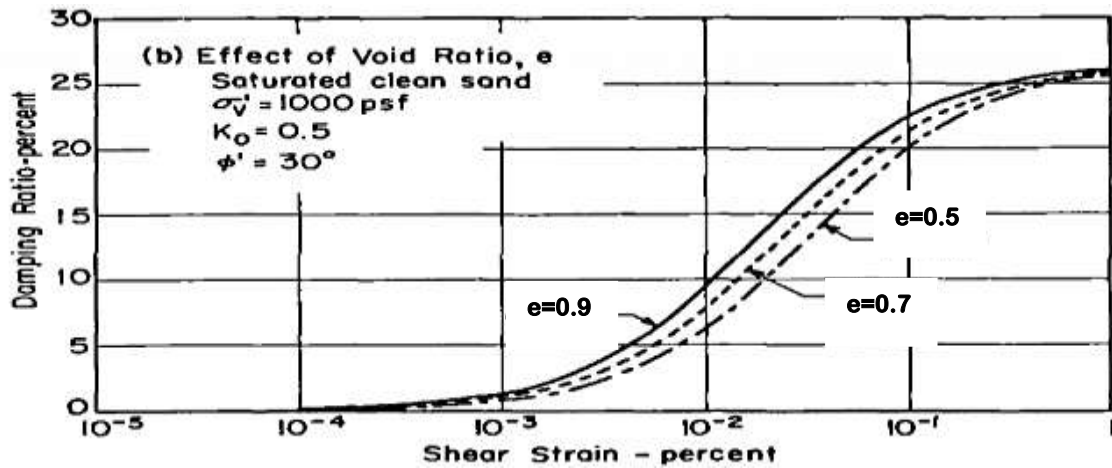


Figure 2.7: Influence of void ratio on damping values for sands (Seed and Idriss 1970)

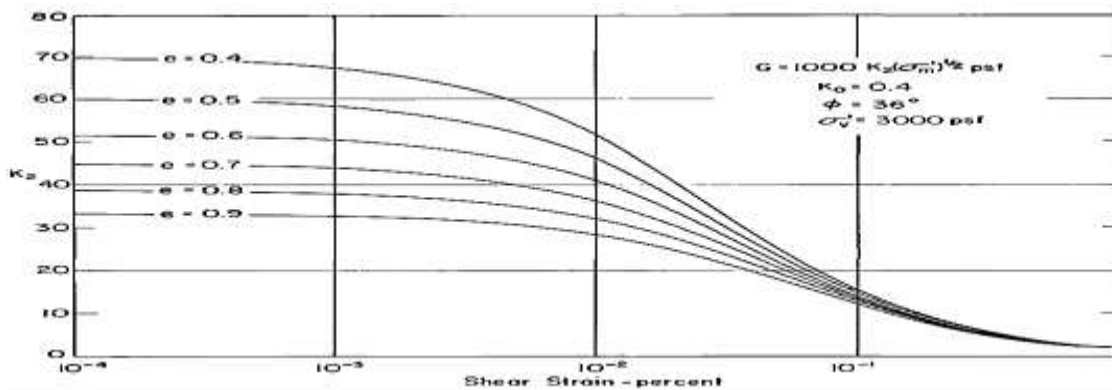


Figure 2.8: Shear modulus of sands at different void ratios (Seed and Idriss 1970)

The effect of various factors on shear modulus, modular ratio and damping values is summarized in Table 2.3 below.

Table 2.4: Effect of increase of various factors on  $G_{max}$ ,  $G/G_{max}$  and damping ratio,  $D$  of normally consolidated and moderately over consolidated clays (Vucetic and Dobry 1987)

Increasing factor	Maximum shear modulus ( $G_{max}$ )	Shear modulus Degradation ( $G/G_{max}$ )	Damping ratio ( $D$ )
Confining pressure ( $\sigma$ )	Increase with $\sigma$	Stays constant or Increases with $\sigma$	Stays constant or decreases with $\sigma$
Void ratio ( $e$ )	Decreases with $e$	Increases with $e$	Decreases With $e$
Geological age ( $t$ )	Increases with $t$	May increase with $t$	Decreases With $t$
Cementation ( $c$ )	Increases with $c$	May increase with $c$	May decrease With $c$
Over consolidation (OCR)	Increase with OCR	Not affected	Not affected
Plasticity index (PI)	Increases with PI if OCR >1; stays about Constant if OCR =1	Increase with PI	Decrease With PI
Cyclic strain ( $\gamma_c$ )	-	Decreases with $\gamma_c$	Increase with $\gamma_c$
Number of loading Cycles ( $N$ )	Decreases after $N$ cycles of Large $\gamma_c$ but recover later with time	Decreases after $N$ cycles of Large $\gamma_c$ ( $G_{max}$ measures before $N$ cycles)	Not Significantly for Moderate $\gamma_c$ And $N$

## 2.5 Values of shear modulus and damping ratio for sand and clay

### 2.5.1 Shear modulus and damping of sands

The shear modulus and damping ratio values for sands are strongly influenced by confining pressure, strain amplitude and void ratio (relative density) but not significantly by the variation in grain size characteristics (Seed and Idriss 1970). Figure 2.9 and 2.10 shows that the value of sand by various researchers.

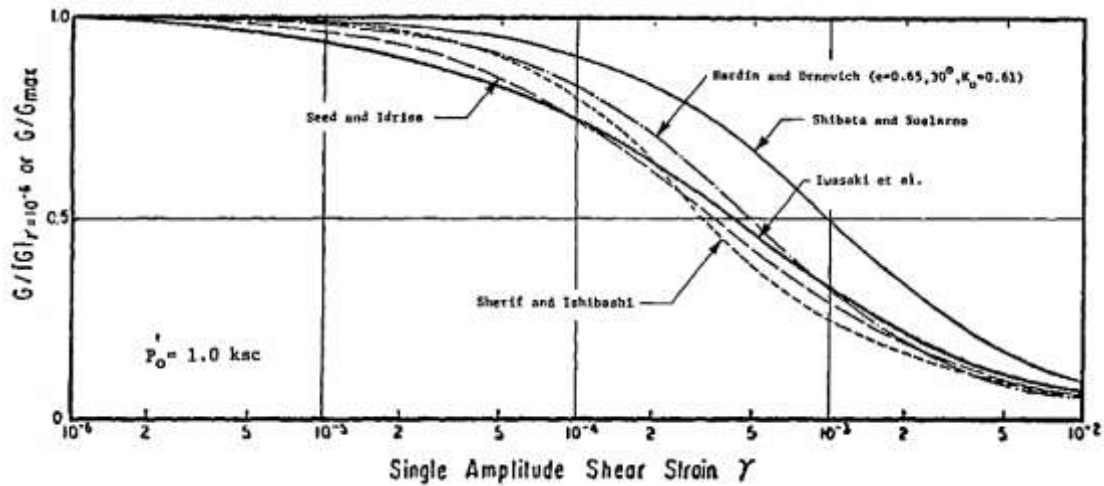


Figure 2.9: Comparison of normalized modulus reduction relationship for sands (Seed et al. 1988)

From their study of factors influencing damping ratio of sands, (Hardin and Drenvich 1972) concluded that shear strain, effective mean principal stress, void ratio and number of cycles were very important while the effect in grain size characteristics were considered to be relatively insignificant as in the case of shear moduli.

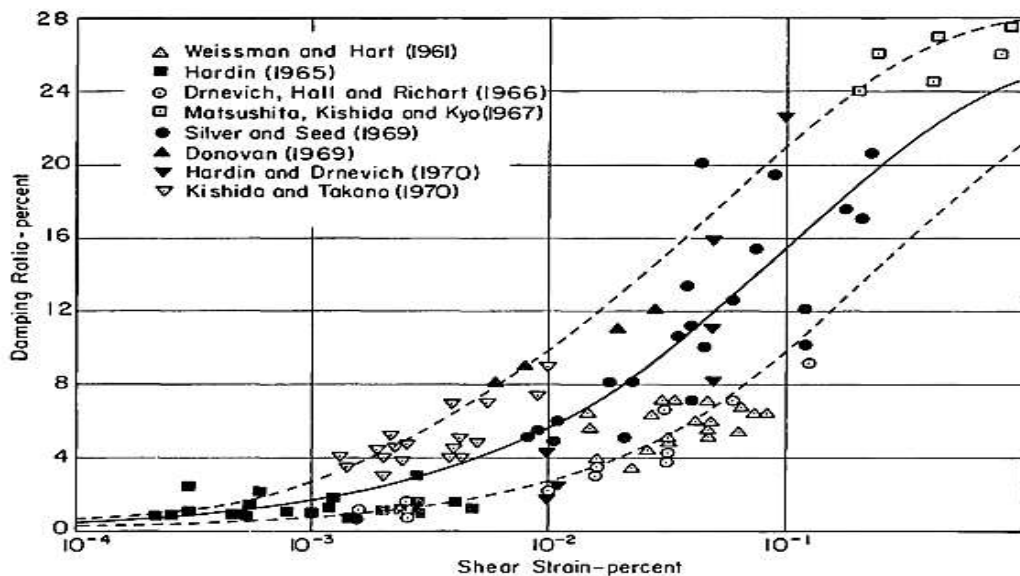


Figure 2.10: Variation of damping ratio for sands (Seed and Idriss 1970)

Furthermore, they noticed that, for vertical confining pressure less than 500 psf, the effect of pressure changes may be significant. This condition represents top few feet of soil. (See Figure 2.11 below)

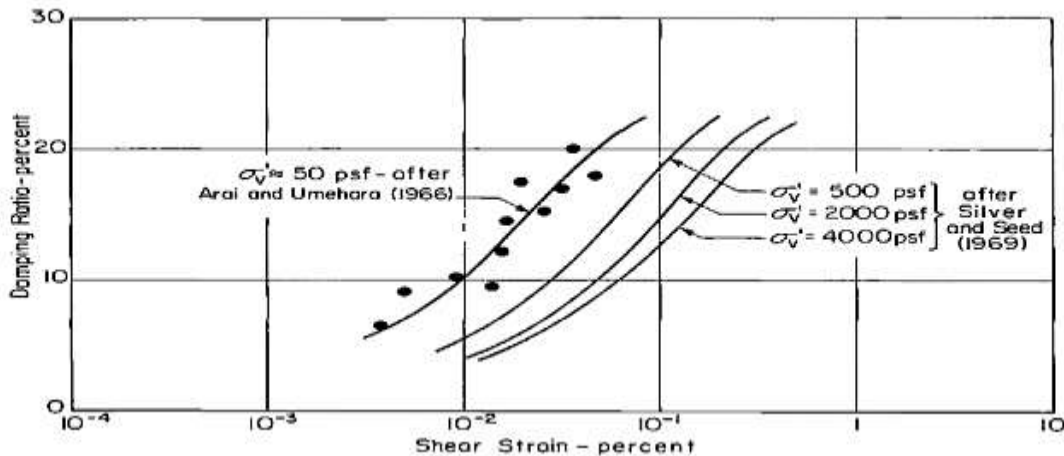


Figure 2.11: Influence of confining pressure on damping ratio of dry sand (Seed and Idriss 1970)

### 2.5.2 Shear modulus and damping of clays

Shear modulus and damping ratio of clays is predominantly affected by shear strain amplitude and sample disturbance. In addition, the values are influenced by relative stiffness and strength of clays.

Accurate determination of the shear modulus of saturated clays is enormously complicated by the large effect of strain amplitude and sample disturbance on the modulus values. In situ measurements eliminate the problem raised by sample disturbance. In the laboratory, on the other hand, samples may be tested under wide range of strains but the moduli determined will inevitably be influenced by the effect of sample disturbance.

The modulus reduction curves for variety of sands shows relatively small variation from one sand to another. However, as seen from Figure 2.12 the modulus reduction curves for clays show a much larger scatter.

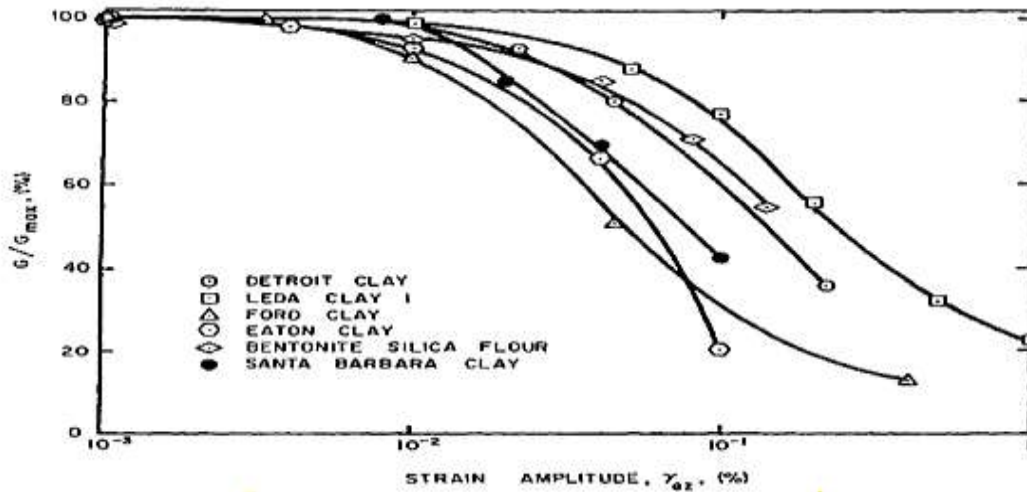


Figure 2.12: Comparison of modulus reduction relationship for clays (Seed et al.1988)

Test data for damping ratios for saturated clays are so limited and the results vary to such extent that it is difficult to determine the main factors influencing the damping ratio of these soils. The relationship between strain levels and damping ratio for any particular soils is shown in Figure 2.13 below. This average relationship may well provide values of damping ratio with sufficient accuracy for many practical purposes.

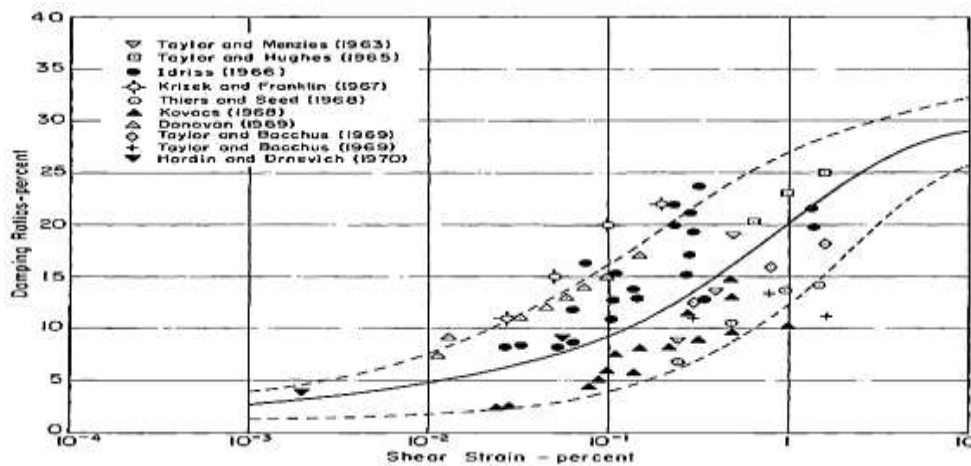


Figure 2.13: Damping ratio for saturated clays (Seed et al .1988)

## 2.6 Estimation of Maximum Shear modulus

Maximum (initial) shear modulus is one of the most important parameters affecting shear modulus, damping ratio and seismic response of soil. The maximum shear modulus also known as the small strain shear modulus (initial shear modulus) is the peak value of the secant shear modulus at very low strain amplitude in elastic range.  $G_{\max}$  could be estimated from shear velocity method using direct field tests or from strain method using laboratory testing or from empirical equations.

The maximum shear modulus,  $G_{\max}$  can be calculated by measuring soils' shear wave velocity  $v_s$  :

$$G_{\max} = \rho v_s^2 \quad (2.2)$$

Where

$G_{\max}$  - is the maximum (initial) shear modulus

$\rho$  - is the density of the soil deposit

$v_s$  - is the shear wave velocity

### 2.6.1 Empirical correlation for estimation of maximum shear modulus

In the absence of reliable shear wave velocity and shear modulus data, empirical correlations play huge role in determination of shear modulus and damping ratio of soils. These relations are usually expressed in terms of normalized shear modulus ( $G/G_{\max}$ ). The maximum shear modulus is used to normalize the shear modulus versus shear strain relationships. These relationships allow the engineer to use well established degradation curves and scale them to measure in situ value of  $G_{\max}$ .

As seen from Table 2.5, following the work of (Hardin and Drnevich 1972) many researchers developed empirical relations to estimate  $G_{\max}$  of the following general form:

$$G_{\max} = A\sqrt{\sigma'_m}OCR^K f(e) \quad (2.3)$$

Where  $f(e)$  - is some function of the void ratio,  $e$

OCR - is the overconsolidation ratio

A - is the normalizing constant

K - is the power factor

$$\sigma'_m \text{ - is the mean principal effective stress, } \sigma'_m = \left[ \frac{1 + 2K_o}{3} \right] \sigma'_v$$

$\sigma'_v$  - effective vertical stress

$K_o$  - coefficient of at rest lateral earth pressure

Table 2.5: Correlation for estimation of maximum (initial) shear modulus (Ishihara 1996)

Reference	Correlation	Units	Limitation
(Seed et al. 1984)	$200(K_2) \times \sqrt{\sigma'_m}$ $(K_2)_{\max} = 20(N_1)^{60/3}$	kPa	$(K_2)_{\max} = 30$ For very loose sands and 75 for dense sands; 80-180 for dense well graded gravels.
(Imai and Tonouchi 1982)	$G_{\max} = 15560(N_{60})^{0.68}$	kPa	Limited to cohesionless soils
(Hardin 1978)	$G_{\max} = \frac{625(P_a \times \sigma'_m)^{0.5 \times \text{OCR} \times K}}{0.3 + 0.7e^2}$	kPa	Limited to cohesionless soils Pa-atmospheric pressure
(Jarniolkowski 1991)	$G_{\max} = \frac{625(P_a \times \sigma'_m)^{0.5 \times \text{OCR} \times K}}{e^{1.3}}$	kPa	Limited to cohesive soils Pa-atmospheric pressure
(Mayne and Rix 1993)	$G_{\max} = \frac{99.5(P_a) \times 0.305 \times (q_c)^{0.695 \times \text{OCR} \times K}}{e^{1.13}}$	kPa	Limited to cohesive soils

Hardin and Drnevich (1970) studied factors that influence shear modulus and damping ratio of soils and obtained an empirical expression for evaluation of maximum shear modulus. This expression is based on basic properties of a soil.

$$G_{\max} = 14760 \times \frac{(2.973 - e)^2 \times OCR^a \times \sqrt{\sigma'_m}}{(1 + e)} \quad (2.4)$$

Where  $G_{\max}$  - is the maximum shear modulus in psf

OCR - is the overconsolidation ratio

a - is a parameter that depends on plasticity of soils

$\sigma'_m$  - is the mean effective principal stress given by  $\sigma'_m = \frac{\sigma'_1 + \sigma'_2 + \sigma'_3}{3}$  (in psf)

For at rest, i.e. condition  $\sigma'_3 = \sigma'_2$  with  $K_0 = 0.5$ ,  $\sigma'_m = \frac{2}{3} \times \sigma'_1$

Overconsolidation ratio (OCR) =  $\frac{\sigma'_c}{\sigma'_p}$

Table 2.6: Value of “a” which depends on plasticity of the soils

PI	a
0	0
20	0.18
40	0.30
60	0.41
80	0.48
≥ 100	0.50

## CHAPTER THREE

### 3 Overview of Study Area and Experimental Methods

#### 3.1 Area of study

Yeka sub-city is located in the North East part of Addis Ababa city. The total area of the sub-city is 85.98 km<sup>2</sup> and it is estimated that 4,285 people live in one square kilometer. The subcity is characterized by variable topographic features from flat to, hilly and mountainous terrain. Yeka is one of the 10 sub cities of Addis Ababa with 13 woredas under it.

The most common shallow geological formations in Yeka subcity includes elastic silt soils, plastic clay soils, weathered and intact rock formation. Table 3.1 shows the coordinates of the test pits. Figure 3.1 and 3.2 indicate location of the test pits.

Table 3.1: Coordinate for Test Pits

Label	N	E
Test pit 1	9 <sup>0</sup> 01' 06.00''	38 <sup>0</sup> 48' 04.95''
Test pit 2	9 <sup>0</sup> 01' 19.87''	38 <sup>0</sup> 47' 03.03''
Test pit 3	9 <sup>0</sup> 01' 20.77 ''	38 <sup>0</sup> 51' 01.85 ''
Test pit 4	9 <sup>0</sup> 02' 10.43 ''	38 <sup>0</sup> 46' 48.88 ''
Test pit 5	9 <sup>0</sup> 03' 48.88''	38 <sup>0</sup> 46' 27.87''
Test pit 6	9 <sup>0</sup> 01' 18.00''	38 <sup>0</sup> 52' 28.15''
Test pit 7	9 <sup>0</sup> 02' 44.41''	38 <sup>0</sup> 51' 02.56 ''
Test pit 8	9 <sup>0</sup> 02' 46.00''	38 <sup>0</sup> 52' 33.25''

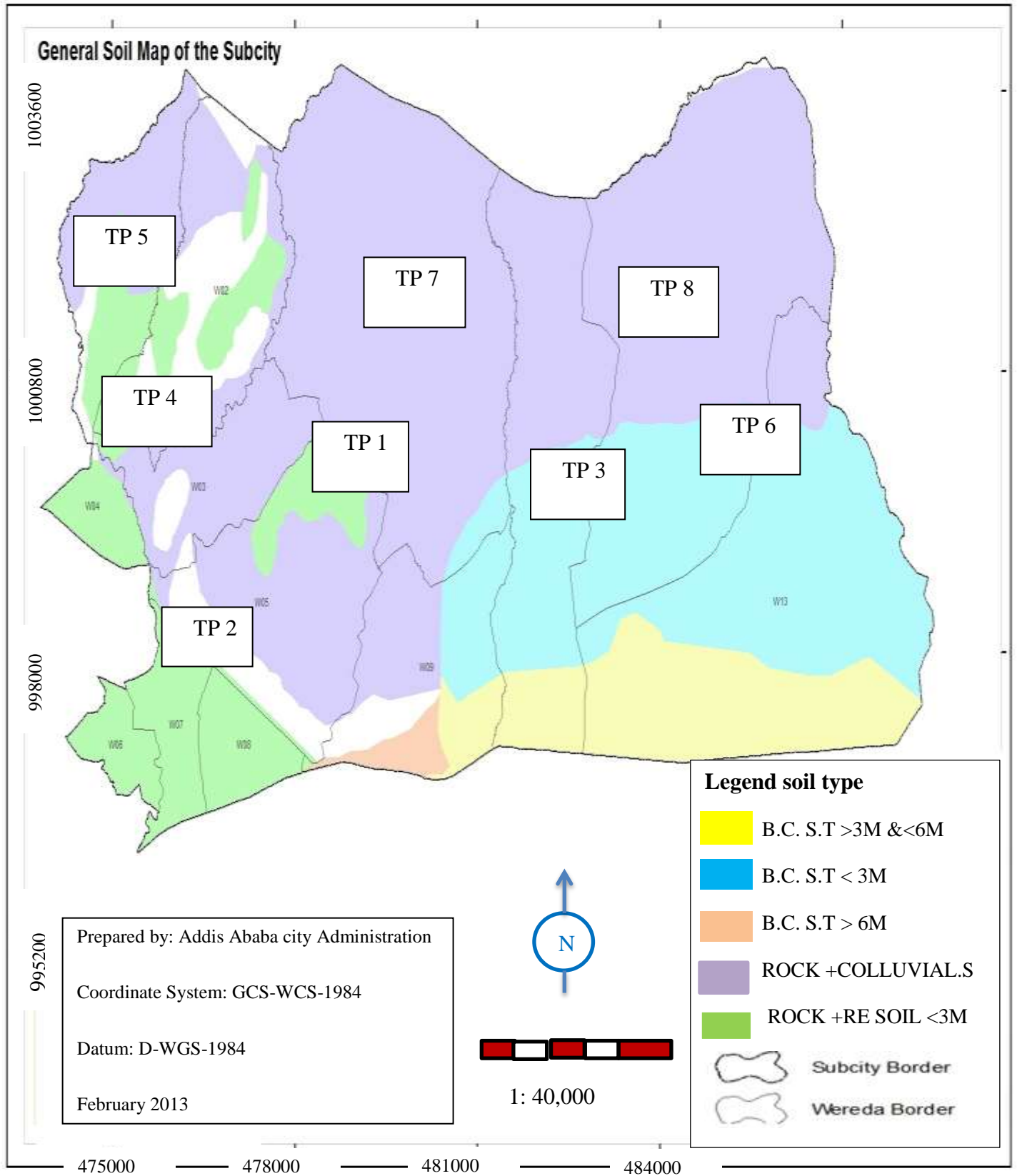


Figure 3.1: Map of the Subcity

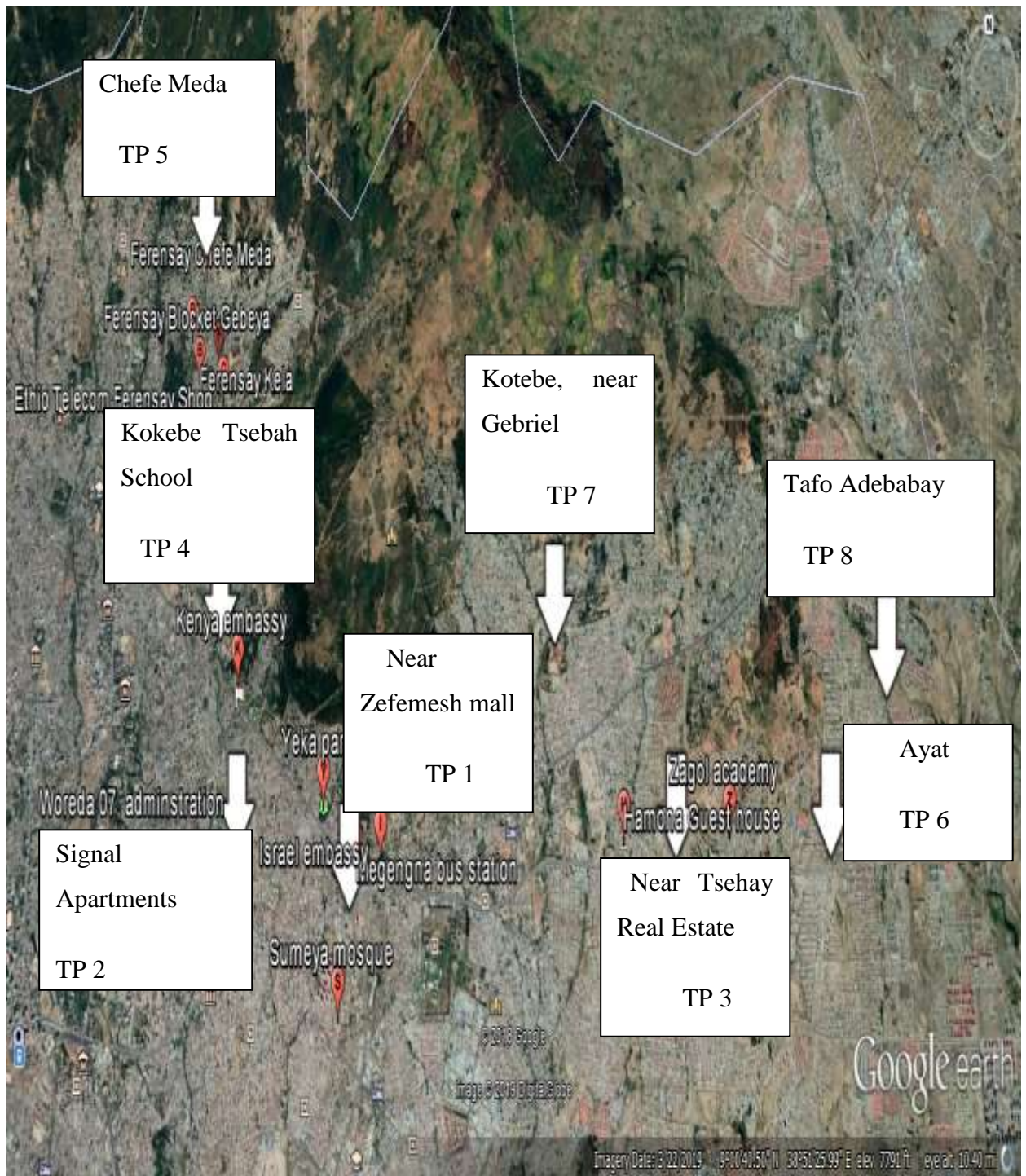


Figure 3.2: Location of Test Pits

## **3.2 Experimental Techniques**

### **3.2.1 Sample collection and methods**

All soil samples were taken from 8 selected test pits which are located as shown in Figure 3.1 and 3.2 above. Since only soil samples can be tested under cyclic simple shear machine, areas which are characterized by intact rock formations have been omitted. The field density is determined using core cutter method. The dynamic tests are performed on undisturbed samples obtained from the test pits. Grain size distribution and index properties of the soils are also determined.

Eight test pits were excavated using local labor, and samples were collected from each test pit at 2.50 m depth different parts of the subcity. Disturbed and undisturbed soil samples were collected from test pits to determine index properties, soil classification, shear modulus and damping ratio values. Tube sampling techniques are used to extract undisturbed soil as per ASTM D1587-94 specification in different area of the subcity. Polythene bag is used for sampling and transporting representative disturbed soil samples according to ASTM D 4220-95

## **3.3 Testing Apparatus**

Some of the laboratory tests available to measure the dynamic properties of soils at different strain levels include resonant column test, travel time test, ultrasonic pulse test, piezoelectric bender element test and cyclic simple shear test. For this study, the cyclic simple shear test is used.

### **3.3.1 Cyclic simple shear test**

The Cyclic shear device consists either of a rectangle box made of hinged plates or a cylindrical wire-reinforced membrane which surrounds the sample and restrains the sample from expanding laterally in all direction during consolidation stage, but allows the sample to deform horizontally during the cyclic loading test. The apparatus uses electronic reading system. An electronic reading system records lateral force and displacement, axial force and displacement. This electronic reading system is governed by UTS004 software application program that incorporates the functionality to perform consolidation and cyclic simple shear (Wykeham Farrance 2003).

The simple shear device consists of a feature that is arranged for applying a constant vertical load and a mechanism for applying a horizontal cyclic shear load. Cyclic shear testing is considered to be appropriate to evaluate dynamic property of soils in the laboratory because it closely replicates the field loading condition due to the vertical propagation of shear waves during earthquake shaking.



Figure 3.3: The cyclic shear testing apparatus at AAIT Geotechnical laboratory (See appendix J)

### 3.3.2 Sample preparation

For the cyclic shear test, undisturbed samples were retrieved from test pits are used. A cylindrical shape undisturbed sample of 20 mm height and 70 mm diameter was prepared. Then, the sample is positioned on a pedestal with top cap. The sample is supported by a rubber membrane placed and secured with brass rings.

These rings restrain the sample through consolidation stage and permit lateral displacement during cyclic shear stage.

### **3.3.3 Consolidation stage**

The consolidation stage is merely the application of a static axial loading stress to the specimen while the lateral loading (shear) axis is held stationary. Axial stress and specimen displacements (axial and lateral) are measured overtime and logged by the system. Logged data are also displayed to the operator in the form of charts and tables as the test stage proceeds.

The test was conducted with different axial stress. This is to account for the effect of the varying magnitude of axial stress on damping ratio and shear modulus values and to compare the results with literature values. In this study, the axial stresses applied during consolidation stage are selected to be 100, 200 and 400 kPa. The consolidation stage is manually terminated by the operator once the rate of vertical strain is less than 0.05 % per hour (NORSOK standard 2004).

### **3.3.4 Cyclic simple shear stage**

The cyclic shear stage of the test applies a lateral cyclic shear displacement to the specimen. The test is conducted by applying a lateral cyclic shear strain of specified amplitude to the specimen, while the vertical height of the specimen is maintained as specimen displacements are measured for each loading cycle. Both axial and lateral force and specimen displacement are measured for each loading cycle.

The lateral cyclic shear force tends to slide the rings over each other. However, the volume of the specimen remains constant. The lateral force and displacement for 50 sample points is measured for each loading cycle. Both axial and lateral forces are measured for each loading cycle using linear variable differential transducers (LVDT).

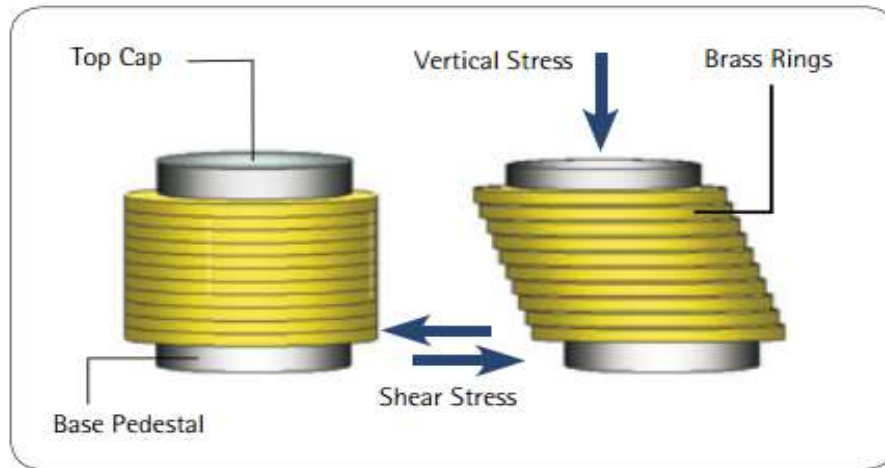


Figure: 3.4 Shear stage (Wykeham Farrance 2003).

The applied selected shear strain and corresponding amplitude is shown in Table 3.2

Table 3.2: Selected amplitude and corresponding shear strain for cyclic shear test

Shear strain (%)	Amplitude (mm)
0.01	0.002
0.1	0.02
1	0.2
2.5	0.5
5	1

The shear strain and the corresponding amplitudes are related according to the following Equation 3.1.

$$\text{Shear strain (\%)} = \frac{\text{Amplitude (A)}}{\text{Height of sample (H)}} \times 100 \% \quad (3.1)$$

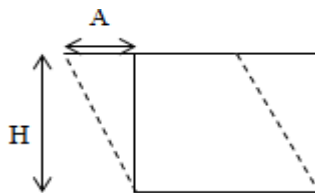


Figure 3.5: Conversion of shear strain percentage to corresponding amplitude

## CHAPTER FOUR

### 4 Analysis and Presentation of Test Results

#### 4.1 Summary of laboratory and field test results

The following laboratory and field tests are conducted.

- Particle size analysis
- Atterberg limits
- In-situ density and moisture content
- Specific gravity
- Consolidation
- Cyclic simple Shear test

All tests were conducted according to ASTM procedures. ASTM D422 standard test method for particle size analysis of soils, ASTM D854- standard test for specific gravity of soil solids by water pycnometer, ASTM D2435 Standard test method for one dimensional consolidation properties of soils, ASTM D2937 Standard test method for in situ density, ASTM D4318- standard test for liquid limit, plastic limit and plastic index of soils and ASTM D3999 for Cyclic simple shear test.

#### 4.2 Laboratory test results

##### 4.2.1 Grain size distribution

Sieve analysis is performed to determine the distribution of coarser and large sized particles and for fine grained soils, hydrometer analysis is used. Based on particle size distribution, soils in Yeka subcity are categorized as fine grained soils. A summary of particle size distribution curves is show in Figure 4.1 below.

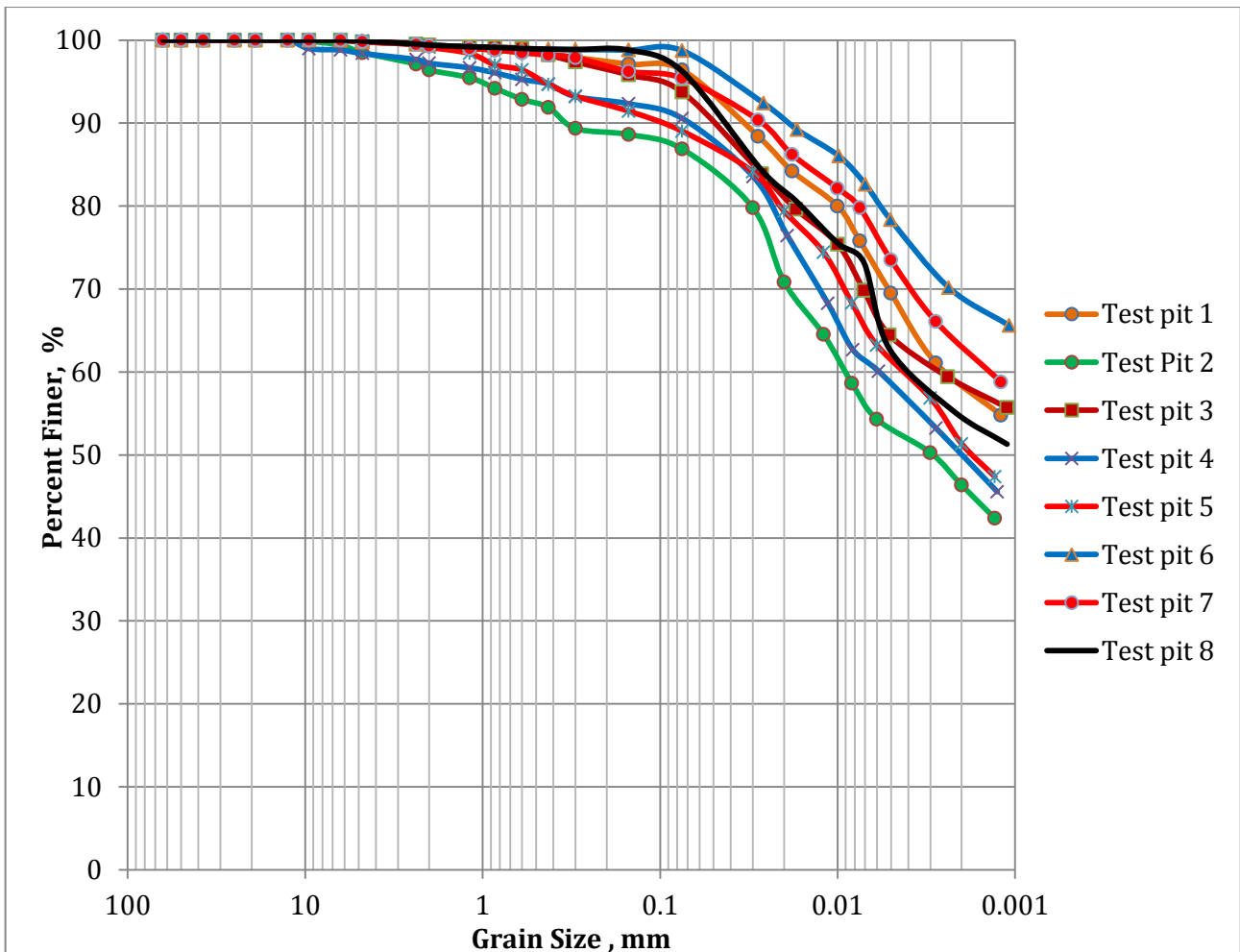


Figure 4.1: Particle size distribution curve for all test pits (See Appendix C- for combined particle size analysis result)

In addition to particle size, moisture content significantly influences the properties of fine grained soils. In USCS, size of soil particles in conjunction with consistency of the soil is used to classify soils.

To differentiate the plasticity and organic characteristics of fine grained soils, the plasticity chart is used. As seen from Figure 4.2, with the exception of Test Pit 7 and 8 all test samples fall on or above the “A” line.

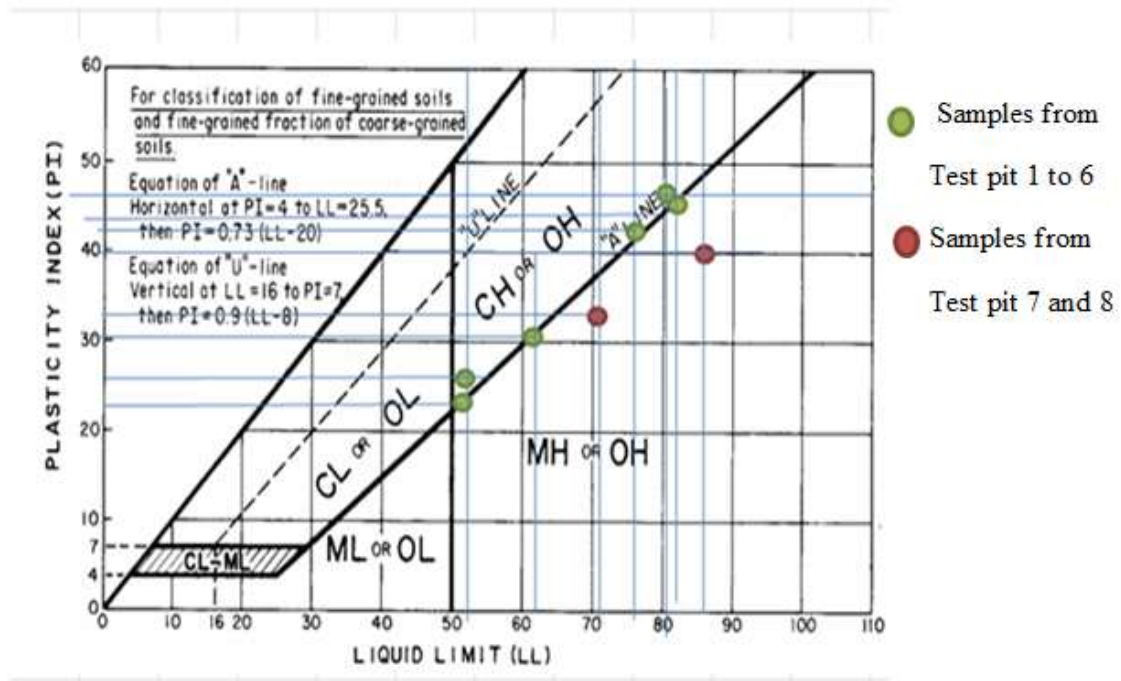


Figure 4.2: Plasticity Chart

#### 4.2.2 Index properties of soils

The behavior of soils should be understood by conducting tests on physical characteristics of the soil particles and their constituents. The physical properties of soils which serve mainly for identification and classification purpose are commonly known as index properties. Such properties can be determined by simple laboratory tests. These tests are conducted according to ASTM D4318. The results are presented in Table 4.1. Although Test pit 7 and 8 have high liquid limit and might have the tendency to be clay, their value on plasticity chart is below "A" line and hence are classified as elastic silt. (See Figure 4.2)

Table 4.1: Index properties result of all test pits

Label	Liquid limit(LL)	Plastic limit (PL)	Plasticity index PI=(LL-PL)	Specific gravity (Gs)
Pit 1	80	35	45	2.68
Pit 2	53	28	25	2.66
Pit 3	76	35	41	2.69
Pit 4	56	33	23	2.66
Pit 5	62	32	30	2.68
Pit 6	83	41	42	2.70
Pit 7	71	38	33	2.61
Pit 8	85	45	40	2.71

#### 4.2.3 Soil classification

The Practice of systematic categorizing of soils in different groups for engineering purposes based on laboratory determination of particle size, liquid limit and plasticity index is known as Unified Soil Classification System. The USCS is based on the recognition of the type and the predominance of the constituents, considering gradation and plasticity.

Table 4.2: Classification of soils according to UCS

Sample from test	Percentage of particles Passing No 200 sieve	Characteristics of soils passing sieve No.40			On Plasticity Chart	USCS Classification
		Liquid Limit	Plastic limit	Plasticity Index		
Pit 1	96.4	80	35	45	Above A line	CH
Pit 2	86.87	53	28	25	Above A line	CH
Pit 3	93.74	76	35	41	On A line	CH
Pit 4	90.57	56	33	23	On A line	CH
Pit 5	89.01	62	32	30	On A line	CH
Pit 6	98.74	83	41	42	On A line	CH
Pit 7	95.4	71	38	33	Below A line	MH
Pit 8	96.23	85	45	40	Below A line	MH

#### 4.2.4 One dimensional Consolidation test result

Consolidation characteristics of the soils were determined by one-dimensional oedometer apparatus. The main reason for conducting this test is to understand the stress history and to use value of pre consolidation pressure, which is one of the parameters used to compute the maximum shear modulus. According to USCS, the soils in Yeka subcity are categorized elastic silt and plastic clay .Two representative test pits (test pit 6 and test pit 8) were chosen for consolidation test. The consolidation test results are shown in Figure 4.3 and 4.4 below. The overconsolidation ratio is expressed as:

$$OCR = \frac{\sigma'_c}{\sigma'_p} \quad (4.1)$$

Where  $\sigma'_c$  - is the preconsolidation pressure of a specimen

$\sigma'_p$  - is the present effective vertical stress

Table 4.3 OCR value of the tested soils

	Silt soil			Clay soil		
$\sigma'_p$	100	200	400	100	200	400
$\sigma'_c$	184	184	184	210	210	210
OCR	1.84	0.92	0.46	2.1	1.05	0.525

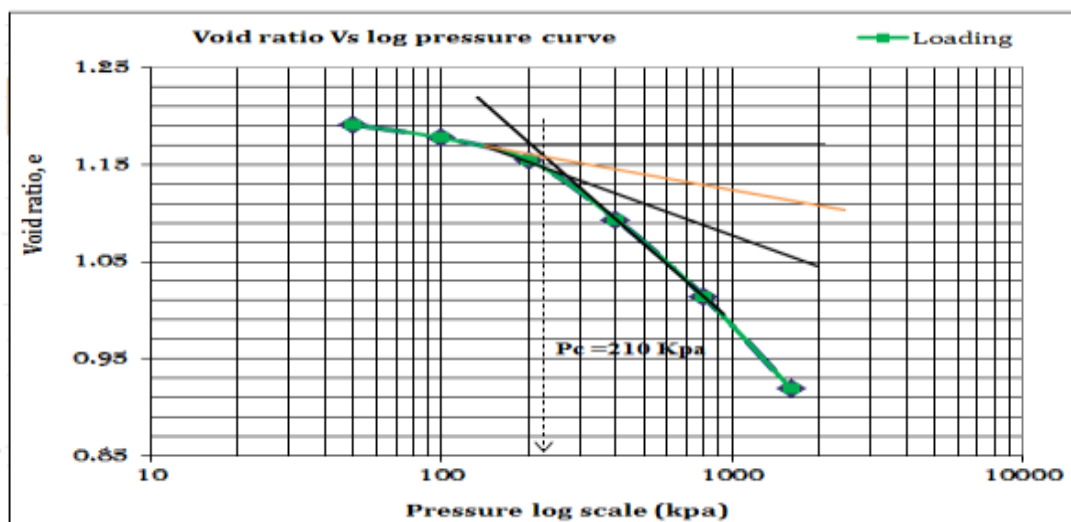


Figure 4.3: Void ratio versus Pressure log scale, kPa. (Test pit 6, Pc=210 kPa)

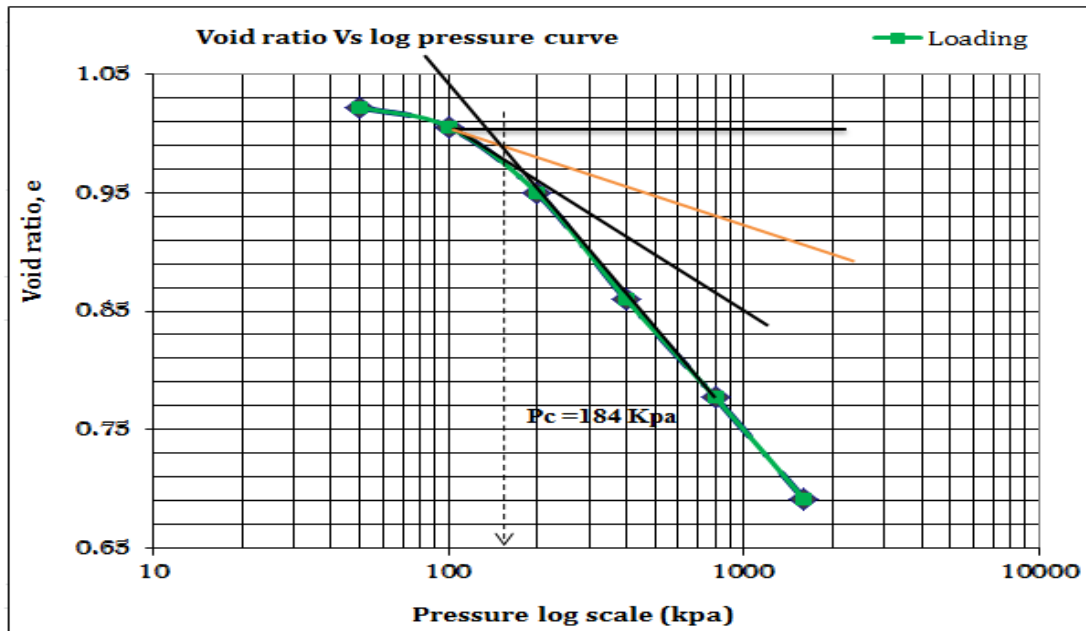


Figure 4.4: Void ratio versus Pressure log scale, kPa. (Test pit 8,  $P_c = 184$  kPa)

#### 4.2.5 Determination of shear modulus and damping ratio values

Hysteretic stress- strain relationships are determined in the laboratory by means of simple shear test under cyclic loading conditions. The hysteresis loops of each cycle can be plotted using the shear stress and strain values obtained from 50 sample points in a cycle. These sample point's shear stress and shear strain values in a cycle have been evaluated for the determination of shear modulus and damping ratio values of the hysteresis loop. Then hysteresis loop of each cycle can be plotted using the results of shear strains and shear stresses that can be computed and presented using spreadsheet program. In most seismic events, the number of significant cycles is likely to be less than 20. The values determined at 5 cycles are likely to provide reasonable values for all practical purposes (Das 2006).

$$\text{Shear strain , } \gamma = \frac{\text{Lateral Lvdt(displacement)}}{\text{Height of sample after consolidation}} \quad (4.2)$$

$$\text{Shear stress , } \tau = \frac{\text{Shear force}}{\text{Area of sample}} \quad (4.3)$$

$$\text{Area of the sample} = \frac{\pi \times 70^2}{4} = 3848.5\text{mm}^2$$

The shear modulus and Damping ratio of the hysteresis loop can be calculated using the following Equation 4.4 and 4.5.

$$\text{Shear modulus, } G = \frac{\tau_{\max} - \tau_{\min}}{\gamma_{\max} - \gamma_{\min}} \quad (4.4)$$

$$\text{Damping ratio, } D = \frac{\text{Area of loop}}{4 \times \pi \times \text{Area of } \Delta} \quad (4.5)$$

Typical computation of shear stress and shear strain for each cycle is shown in Table 4.3. Using the shear stress and shear strain values shown in Table 4.3 below, a hysteresis loop for test pit 1 for the 5<sup>th</sup> cycle is plotted. (See Figure 4.6)

Table 4.4: Typical tabulation for shear strain and shear stress values (TP1, 5 % strain and 400 kPa)

Cycle	Time (sec)	Lateral LVDT (mm)	Lateral Force (KN)	Shear strain ( $\gamma$ ) $\frac{\text{Lat.Lvdt(displ)}}{18.382}$	Shear stress ( $\tau$ ) $\left(\frac{\text{Lat.Force}}{A}\right) \times 10^3$ (MPa)	$G_{\tan} = (\tau_i - \tau_{i+1})(\gamma_i + \gamma_{i+1})$
5	0	2.819	0.20565	-0.00135589	0.03486813	-1.1448E-05
	0.038	2.884	0.27588	0.00198323	0.053116799	-0.000276166
	0.076	2.977	0.39751	0.00675494	0.08472132	-0.000591024
	0.114	3.095	0.51398	0.01277417	0.114985059	-0.000739729
	0.152	3.201	0.6059	0.01819673	0.138869689	-0.001004027
	0.19	3.330	0.69582	0.02477478	0.162234637	-0.000728827
	0.228	3.418	0.74769	0.02930057	0.175712615	-0.001050174
	0.266	3.533	0.81038	0.03516897	0.192002079	-0.000487171
	0.304	3.609	0.83564	0.03905414	0.198565675	-0.00077927
	0.342	3.698	0.87192	0.04360908	0.207992724	-1.68578E-05
	0.38	3.755	0.87264	0.04649828	0.20817981	-0.000135661
	0.418	3.796	0.87813	0.04860013	0.20960634	0.000289017
	0.456	3.820	0.86683	0.04983179	0.206670131	0.000267665
	0.494	3.832	0.85656	0.05047088	0.204001559	0.000346338
	0.532	3.839	0.8434	0.05081190	0.200582045	0.000391643
	0.57	3.841	0.82858	0.05089115	0.196731194	0.000324748
	0.608	3.841	0.8163	0.05088348	0.19354034	0.001305984
	0.646	3.830	0.76666	0.05036709	0.180641808	0.004493454
0.684	3.771	0.58962	0.04731172	0.13463947	0.00346268	
0.722	3.704	0.44351	0.04389437	0.096674029	0.003071677	

0.76	3.627	0.30252	0.03995091	0.060038976	0.002275303
0.798	3.410	0.17532	0.02888951	0.026987138	-2.7004E-05
0.836	3.267	0.17738	0.02155938	0.027522411	1.62953E-05
0.874	3.231	0.17586	0.01969886	0.027127452	0.000328581
0.912	3.051	0.13403	0.01053172	0.016258282	0.000264018
0.95	2.998	0.07864	0.00781226	0.001865662	0.000157241
0.988	2.833	-0.00583	-0.00064829	-0.020083149	-0.000106953
1.026	2.753	-0.08262	-0.00471189	-0.040036378	-0.000469652
1.064	2.616	-0.19246	-0.01174344	-0.068577368	-0.000634463
1.102	2.538	-0.28132	-0.01573495	-0.091666883	-0.001244552
1.14	2.395	-0.40497	-0.02300066	-0.123796284	-0.00078778
1.178	2.313	-0.46534	-0.02721918	-0.139482915	-0.001621192
1.216	2.178	-0.56705	-0.03412342	-0.165911394	-0.000587595
1.254	2.097	-0.59829	-0.03826320	-0.174028842	-0.001391914
1.292	1.997	-0.6639	-0.04338258	-0.191077043	0.00025468
1.33	1.932	-0.65302	-0.04670330	-0.188249968	-0.000291218
1.368	1.9	-0.66481	-0.04835625	-0.191313499	-0.000834548
1.406	1.834	-0.69691	-0.05169845	-0.199654411	0.000890648
1.444	1.815	-0.66407	-0.05267600	-0.191121216	0.000669517
1.482	1.811	-0.63966	-0.05288051	-0.184778485	0.000527495
1.52	1.810	-0.62047	-0.05290712	-0.179792127	0.000348558
1.558	1.811	-0.60779	-0.05288358	-0.176497337	0.000365357
1.596	1.812	-0.59449	-0.05283654	-0.173041445	0.001667128
1.634	1.825	-0.53338	-0.05215348	-0.157162531	0.002448309
1.672	1.852	-0.44185	-0.05078889	-0.133379239	0.003116443
1.71	1.894	-0.3212	-0.04861956	-0.102029362	0.003726603
1.748	1.961	-0.16834	-0.04520374	-0.062309991	0.004004564

During the experiment, from the predefined shear shape options, a sinusoidal loading cycle shape had been selected. This shape is the most common type of shape for seismic wave analysis. In addition a loading frequency of 1 Hz is selected, which is common in laboratory tests (Das 1993). Sinusoidal wave shape for 5 % strain and for two cycles is shown in Figure 4.5 below.

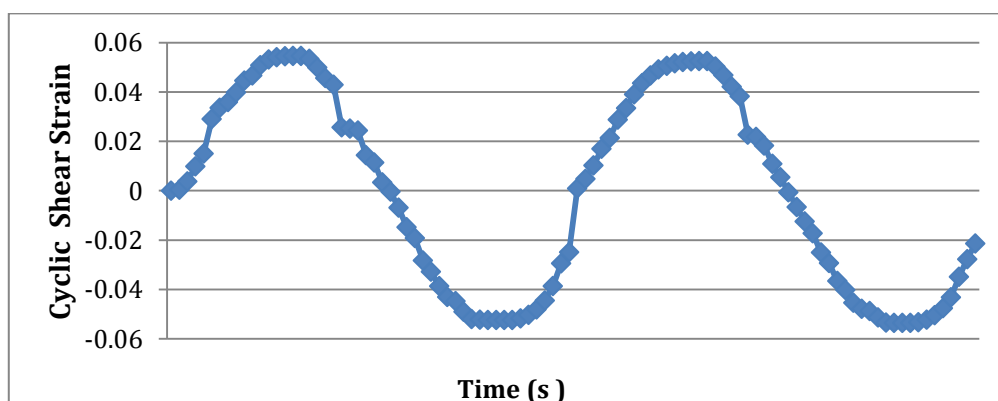


Figure 4.5: Sinusoidal wave shape of 5 % strain for two cycles at 400 kPa axial load

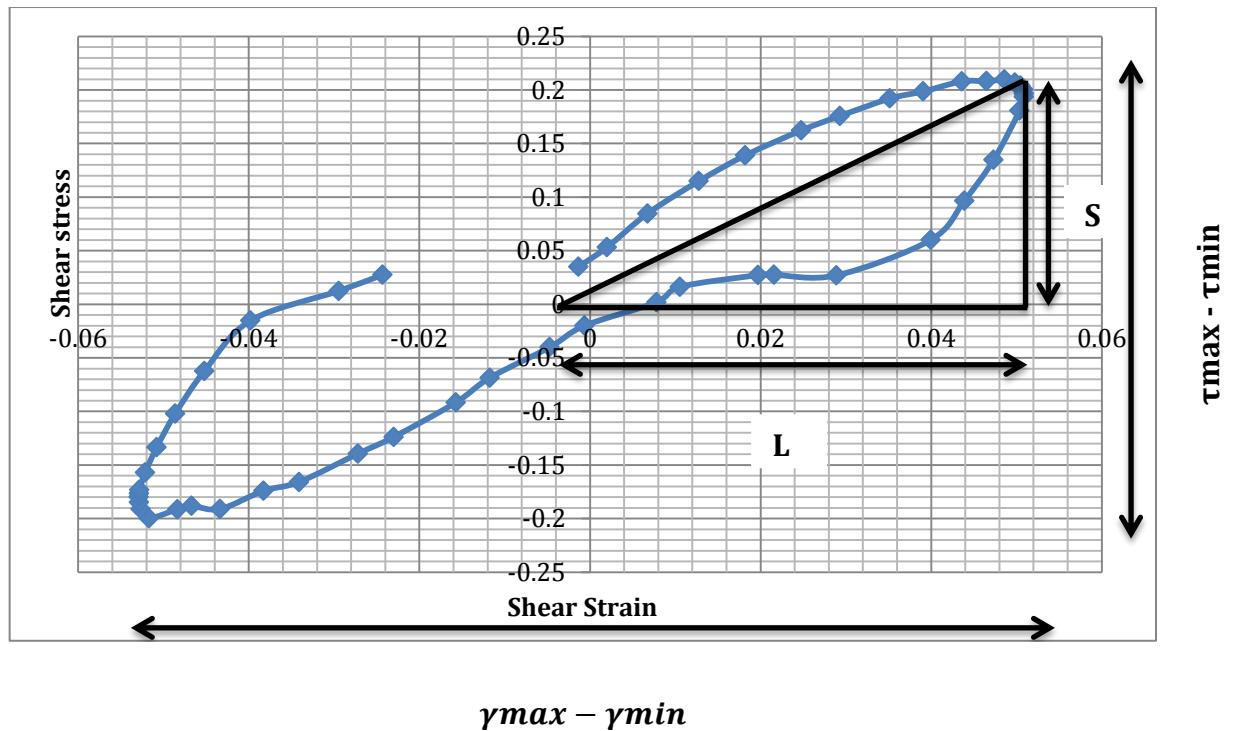


Figure 4.6: Shear stress and shear strain to show hysteresis loop for test pit 1, (5<sup>th</sup> cycle)

Using Table 4.3 and Figure 4.6, the computation of shear modulus, G and damping ratio, D, is presented in Table 4.4 and is carried out according to ASTM 3999.

Table 4.5: Typical calculation for shear modulus and damping ratio

Computation of Shear modulus, G		Computation of Damping Ratio, D	
$\tau_{max}$	0.2096	Area of loop = $0.5 \times \sum (\tau_i - \tau_{i+1}) \times (\gamma_i + \gamma_{i+1})$	0.012
$\tau_{min}$	-0.19996	Area of Triangle = $0.5 \times S \times L$	0.00531
$\tau_{max} - \tau_{min} = 2 \times S$	0.40926		
$\gamma_{max}$	0.050891	$D = \frac{(\text{Area of loop})}{(4 \times \pi \times \text{Area of Triangle})} \times 100\%$	17.985
$\gamma_{min}$	-0.05291		
$\gamma_{max} - \gamma_{min} = 2 \times L$	0.10379		
$G = \frac{(\tau_{max} - \tau_{min})}{(\gamma_{max} - \gamma_{min})}$ in MPa	3.943		

The values for the rest of the cycles are calculated in a similar manner. Hence the shear modulus and damping ratio of test pit 1 under axial load of 100,200 and 400 kPa are given in Table 4.6 to 4.8.

Six test pits were selected to undertake cyclic shear test. Plasticity index was used as selecting criteria. The selected test pits, plasticity index and color of the tested soils by visual identification are shown in Table 4.5 below.

Table 4.6: Soils found in Yeka subcity

Label	Plasticity index	Color
Test pit 1	45	Reddish grey
Test pit 4	23	Red
Test pit 6	42	Black
Test pit 2	25	Black
Test pit 7	33	Red
Test pit 8	40	Black

Table 4.7: Shear modulus and damping ratio values for Test Pit 1 under axial stress of 100 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	16.34	11.55	3.48	1.72	0.57	7.27	10.73	14.56	24.26	31.02
2	16.64	11.78	3.65	1.89	0.74	7.15	10.60	14.42	24.24	30.88
3	16.83	11.86	3.69	1.93	0.94	7.13	10.49	14.28	24.15	30.68
4	16.99	12.01	3.87	2.11	1.03	7.02	10.39	14.17	24.07	30.58
5	17.10	12.18	3.98	2.22	1.11	6.92	10.20	14.06	24.21	30.28
6	17.15	12.25	4.04	2.24	1.18	6.86	10.04	14.15	24.09	29.42
7	17.22	12.27	4.03	2.27	1.18	6.82	9.91	13.38	23.82	29.08
8	17.23	12.29	4.01	2.27	1.18	6.81	9.90	12.92	23.36	28.97
9	17.26	12.26	4.03	2.29	1.19	6.80	9.89	12.83	23.22	28.93
10	17.27	12.30	4.07	2.33	1.31	6.78	9.85	12.71	22.56	28.77
11	17.29	12.27	4.09	2.35	1.31	6.78	9.85	12.61	22.39	28.77
12	17.31	12.32	4.11	2.36	1.31	6.77	9.83	12.59	22.37	28.76
13	17.34	12.38	4.13	2.39	1.31	6.75	9.82	12.57	22.34	28.77
14	17.29	12.29	4.13	2.41	1.31	6.74	9.81	12.56	22.37	28.58
15	17.32	12.35	4.15	2.41	1.33	6.73	9.80	12.28	22.27	28.46
16	17.41	12.35	4.17	2.43	1.37	6.73	9.78	12.35	22.27	28.29
17	17.44	12.26	4.19	2.44	1.37	6.72	9.76	12.23	22.13	28.19
18	17.45	12.32	4.21	2.45	1.35	6.71	9.75	12.47	22.11	28.05
19	17.47	12.33	4.21	2.47	1.35	6.70	9.73	12.33	22.10	27.52
20	17.49	12.31	4.17	2.44	1.37	6.69	9.71	12.33	22.07	27.44
21	17.53	12.29	4.15	2.45	1.37	6.67	9.69	12.26	22.07	27.39
22	17.45	12.42	4.21	2.51	1.37	6.65	9.67	12.24	22.07	27.35
23	17.55	12.41	4.20	2.50	1.41	6.64	9.65	12.17	22.07	27.28
24	17.55	12.32	4.22	2.50	1.41	6.64	9.64	12.21	22.07	27.21
25	17.53	12.31	4.23	2.49	1.41	6.63	9.64	12.33	22.07	27.18
26	17.55	12.30	4.27	2.49	1.41	6.62	9.62	12.27	21.81	27.17
27	17.59	12.33	4.27	2.49	1.41	6.59	9.61	12.26	21.80	27.14
28	17.69	12.31	4.31	2.48	1.41	6.58	9.50	12.24	21.79	27.08
29	17.70	12.32	4.31	2.47	1.41	6.57	9.47	12.17	21.78	26.94
30	17.71	12.37	4.31	2.47	1.42	6.56	9.44	12.21	21.81	26.98
31	17.72	12.43	4.31	2.47	1.40	6.55	9.43	12.18	21.78	26.94
32	17.75	12.41	4.37	2.47	1.43	6.53	9.42	12.12	21.81	26.88
33	17.76	12.40	4.37	2.46	1.43	6.52	9.40	12.07	21.80	26.88
34	17.81	12.38	4.37	2.46	1.43	6.51	9.39	12.07	21.78	26.84
35	17.81	12.43	4.36	2.46	1.43	6.50	9.38	11.47	21.67	26.84
36	17.81	12.38	4.36	2.46	1.43	6.49	9.37	11.43	21.37	26.84
37	17.82	12.39	4.36	2.46	1.44	6.49	9.36	11.55	21.15	26.84
38	17.82	12.42	4.37	2.45	1.44	6.48	9.36	11.59	21.11	26.74
39	17.83	12.42	4.44	2.46	1.44	6.47	9.35	11.63	21.04	26.74
40	17.83	12.45	4.47	2.45	1.45	6.47	9.35	11.74	21.03	26.74

Table 4.8: Shear modulus and damping ratio values for Test Pit1 under axial stress of 200 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	18.05	13.02	6.71	3.23	1.82	5.91	8.42	12.34	19.76	28.69
2	19.47	13.01	6.71	3.28	1.84	5.78	8.35	12.30	19.56	28.64
3	19.56	13.31	6.73	3.31	1.96	5.69	8.29	12.18	19.49	28.46
4	19.57	13.38	6.73	3.43	2.09	5.66	8.21	12.11	19.35	28.36
5	19.56	14.00	7.60	3.47	2.13	5.60	7.09	11.43	18.21	28.03
6	19.56	14.05	7.63	3.51	2.16	5.57	6.84	11.42	18.19	29.01
7	19.55	14.08	7.66	3.56	2.24	5.53	6.84	11.40	18.17	28.99
8	19.55	14.15	7.70	3.59	2.28	5.52	6.83	11.38	18.14	28.81
9	19.54	14.15	7.72	3.60	2.30	5.51	6.82	11.36	18.12	28.79
10	19.53	14.18	7.79	3.62	2.35	5.49	6.81	11.34	18.11	28.64
11	19.53	14.16	7.80	3.62	2.34	5.50	6.79	11.31	18.06	28.60
12	19.52	14.17	7.81	3.65	2.32	5.43	6.75	11.30	18.03	28.54
13	19.51	14.18	7.81	3.65	2.35	5.20	6.78	11.28	18.01	28.53
14	19.50	14.18	7.83	3.67	2.36	4.86	6.75	11.25	17.99	28.36
15	19.48	14.17	7.84	3.68	2.37	4.46	6.71	11.22	17.97	28.22
16	19.45	14.19	7.82	3.69	2.39	4.63	6.69	11.21	17.94	28.09
17	19.43	14.18	7.82	3.70	2.40	4.52	6.65	11.20	17.93	28.05
18	19.43	14.19	7.85	3.72	2.42	4.58	6.62	11.20	17.91	28.00
19	19.43	14.19	7.86	3.74	2.44	4.56	6.59	11.18	17.91	27.93
20	19.40	14.20	7.87	3.75	2.47	4.55	6.57	11.18	17.89	27.93
21	19.39	14.20	7.88	3.75	2.47	4.51	6.50	11.17	17.84	27.82
22	19.39	14.20	7.89	3.76	2.47	4.51	6.48	11.15	17.82	27.81
23	19.37	14.22	7.90	3.77	2.48	4.50	6.42	11.12	17.77	27.80
24	19.36	14.23	7.91	3.78	2.49	4.46	6.38	11.10	17.72	27.78
25	19.36	14.23	7.92	3.79	2.51	4.45	6.34	11.09	17.69	27.68
26	19.33	14.24	7.93	3.80	2.52	4.44	6.33	11.07	17.66	27.65
27	19.33	14.24	7.94	3.81	2.53	4.40	6.32	11.05	17.64	27.64
28	19.29	14.26	7.95	3.81	2.53	4.39	6.30	11.04	17.64	27.62
29	19.26	14.27	7.96	3.83	2.55	4.38	6.29	11.03	17.63	27.62
30	19.26	14.28	7.96	3.84	2.55	4.36	6.29	11.03	17.61	27.59
31	19.25	14.30	7.96	3.85	2.56	4.31	6.28	11.02	17.60	27.58
32	19.20	14.31	7.96	3.86	2.56	4.30	6.27	11.01	17.58	27.57
33	19.19	14.31	7.97	3.88	2.57	4.29	6.25	11.00	17.57	27.56
34	19.15	14.32	7.98	3.88	2.58	4.27	6.24	10.99	17.56	27.55
35	19.10	14.33	7.98	3.89	2.59	4.27	6.21	10.98	17.55	27.53
36	19.09	14.34	7.97	3.90	2.60	4.26	6.20	10.97	17.53	27.52
37	18.99	14.36	7.99	3.91	2.61	4.24	6.19	10.97	17.52	27.51
38	18.91	14.37	7.99	3.92	2.62	4.24	6.18	10.97	17.51	27.49
39	18.88	14.39	8.00	3.93	2.63	4.23	6.17	10.96	17.51	27.48
40	18.88	14.40	8.01	3.94	2.63	4.21	6.16	10.95	17.50	27.48

Table 4.9: Shear modulus and damping ratio values for Test Pit 1 under axial stress of 400 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	24.29	16.79	10.00	5.12	2.80	3.85	6.39	8.55	15.31	18.99
2	24.61	17.09	10.37	5.73	3.50	3.63	6.12	8.42	14.68	18.59
3	24.76	17.48	10.47	5.93	3.70	3.60	5.70	8.41	14.75	18.48
4	24.88	17.72	10.59	5.96	3.86	3.49	5.68	8.30	14.72	18.18
5	25.01	17.89	10.64	5.99	3.94	3.19	5.68	8.26	14.69	17.99
6	25.03	17.95	10.57	5.98	3.98	3.13	5.62	8.19	14.69	17.35
7	25.05	18.00	10.66	5.99	4.01	3.06	5.63	8.00	14.66	17.20
8	25.06	18.00	10.67	5.99	4.12	3.08	5.60	7.77	14.66	17.00
9	25.12	18.01	10.70	6.06	4.13	3.02	5.61	7.53	14.65	16.96
10	25.16	18.09	10.79	6.07	4.13	3.49	5.59	7.50	14.66	17.00
11	25.21	18.11	10.79	6.11	4.13	3.19	5.58	7.27	14.66	16.96
12	25.23	18.16	10.78	6.12	4.13	3.13	5.58	7.19	14.64	16.87
13	25.29	18.16	10.79	6.12	4.14	3.06	5.52	7.07	14.65	16.92
14	25.35	18.19	10.79	6.15	4.18	3.08	5.53	7.00	14.69	16.64
15	25.29	18.17	10.79	6.16	4.20	3.02	5.50	6.91	14.64	16.45
16	25.35	18.21	10.80	6.21	4.19	3.02	5.49	6.77	14.64	16.47
17	25.35	18.22	10.82	6.26	4.19	2.98	5.48	6.65	14.62	16.47
18	25.37	18.25	10.83	6.27	4.20	2.92	5.39	6.64	14.60	16.46
19	25.42	18.26	10.87	6.32	4.23	2.92	5.33	6.54	14.61	16.45
20	25.40	18.36	10.97	6.27	4.23	2.88	5.19	6.52	14.54	16.38
21	25.43	18.40	10.99	6.30	4.24	2.86	5.17	6.49	14.32	16.30
22	25.43	18.42	11.00	6.31	4.24	2.86	5.07	6.48	14.30	16.04
23	25.45	18.44	11.01	6.34	4.25	2.80	5.03	6.51	14.22	16.03
24	25.50	18.49	11.02	6.33	4.26	2.83	4.99	6.47	14.17	15.96
25	25.48	18.51	11.08	6.34	4.27	2.78	4.96	6.45	14.15	15.73
26	25.50	18.51	11.10	6.32	4.27	2.79	4.96	6.45	14.19	15.66
27	25.51	18.52	11.18	6.35	4.27	2.80	4.98	6.37	14.16	15.65
28	25.50	18.54	11.22	6.34	4.29	2.75	4.92	6.39	14.08	15.66
29	25.52	18.59	11.30	6.33	4.28	2.73	4.90	6.34	14.08	15.67
30	25.56	18.60	11.29	6.35	4.28	2.67	4.87	6.27	14.05	15.65
31	25.61	18.62	11.27	6.38	4.28	2.67	4.88	6.24	14.04	15.59
32	25.59	18.65	11.25	6.39	4.29	2.67	4.88	6.30	14.03	15.62
33	25.62	18.66	11.25	6.40	4.29	2.62	4.85	6.20	14.01	15.58
34	25.66	18.67	11.24	6.41	4.31	2.60	4.80	6.17	13.91	15.54
35	25.67	18.68	11.23	6.42	4.31	2.63	4.80	6.30	13.84	15.56
36	25.72	18.69	11.23	6.42	4.32	2.66	4.77	6.20	13.72	15.56
37	25.72	18.69	11.22	6.43	4.32	2.60	4.71	6.17	13.56	15.52
38	25.75	18.71	11.21	6.44	4.33	2.58	4.71	6.19	13.38	15.52
39	25.76	18.72	11.21	6.45	4.34	2.54	4.67	6.19	13.21	15.50
40	25.78	18.72	11.20	6.45	4.34	2.39	4.65	6.10	13.21	15.49

### 4.3. Effect of shear strain level on shear modulus and damping ratio values

As it can be seen from Figure 4.7 and 4.8 below, the magnitude of shear modulus decreases with increasing amplitude of shear strain. On the contrary, the damping ratio value increases with increasing strain amplitude.

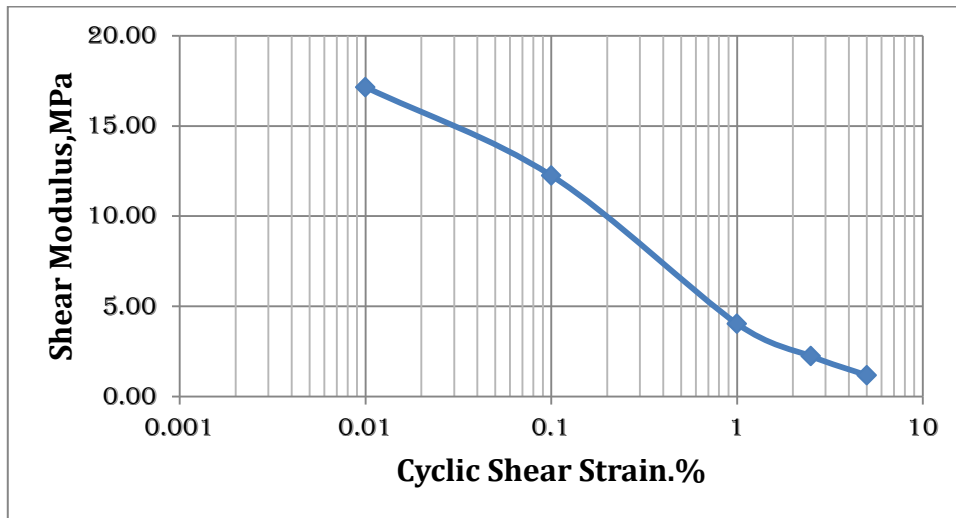


Figure 4.7: Effect of strain level on shear modulus for Test Pit 1, (100kPa)

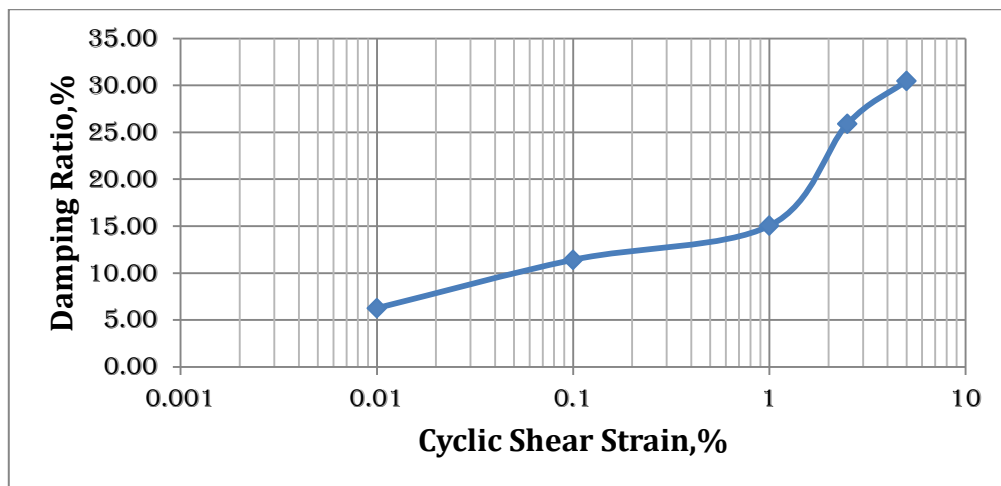


Figure 4.8: Effect of strain level on damping ratio values for Test Pit 1, (100kPa)

### 4.3.1 Variation of shear modulus and damping ratio for selected cycles

The variation of shear modulus and damping ratio of test pit 1, for selected cycles is shown in Figures 4.9 to 4.14 below.

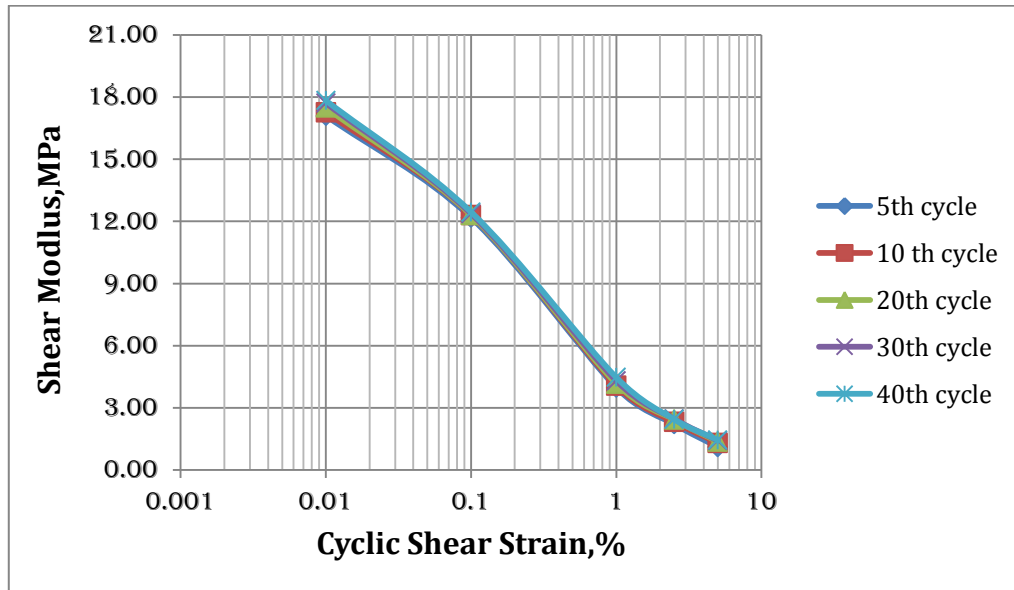


Figure 4.9: Variation of shear modulus with shear strain for different cycles for Test Pit 1 under axial stress of 100kPa

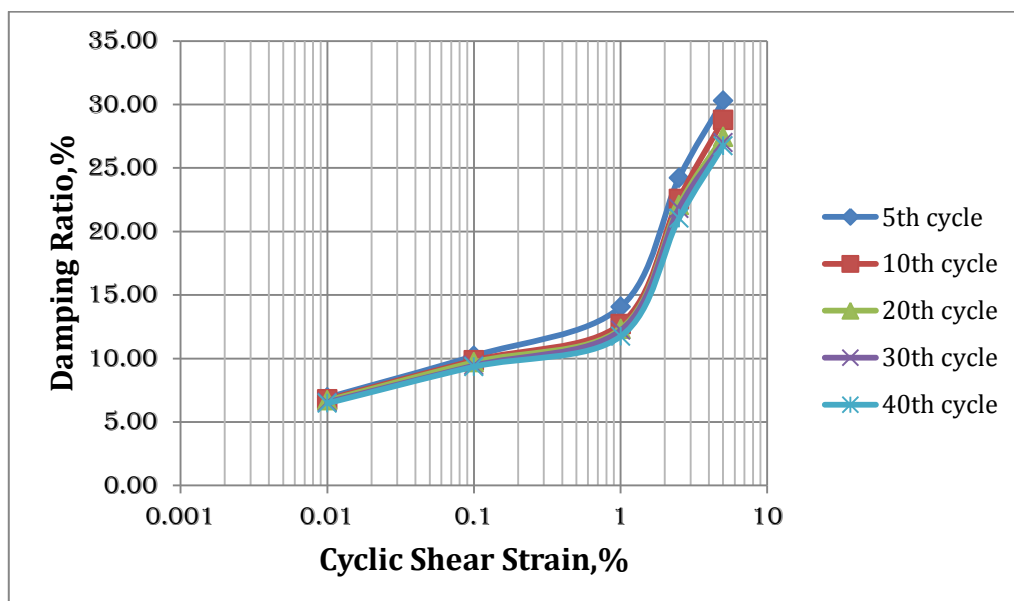


Figure 4.10: Variation of damping ratio with shear strain for different cycles for Test Pit 1 under axial stress of 100kPa

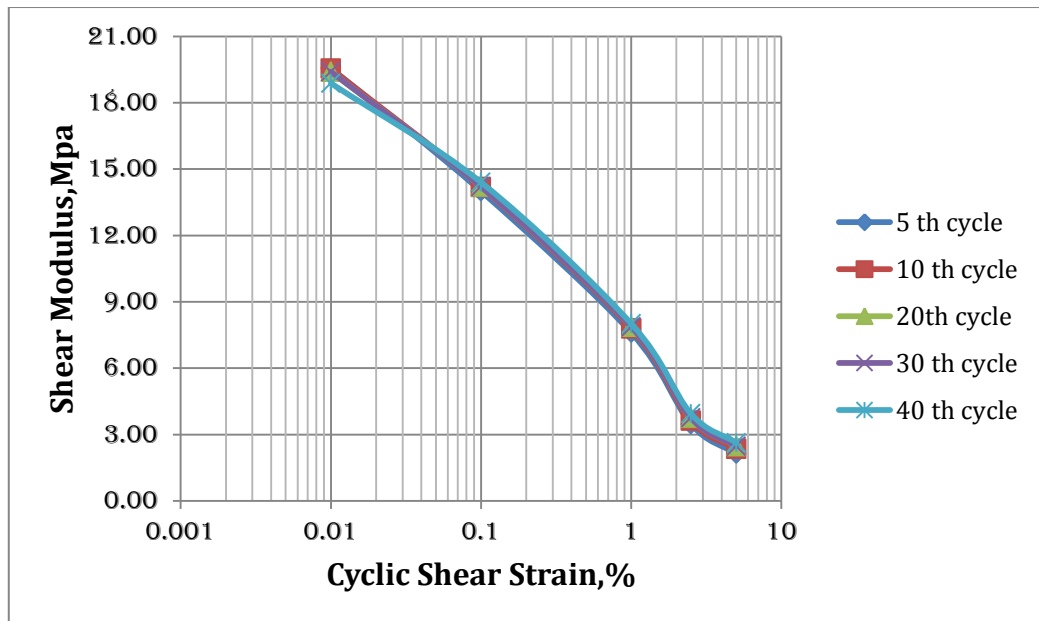


Figure 4.11: Variation of shear modulus with shear strain for different cycles for Test Pit 1 under axial stress of 200kPa

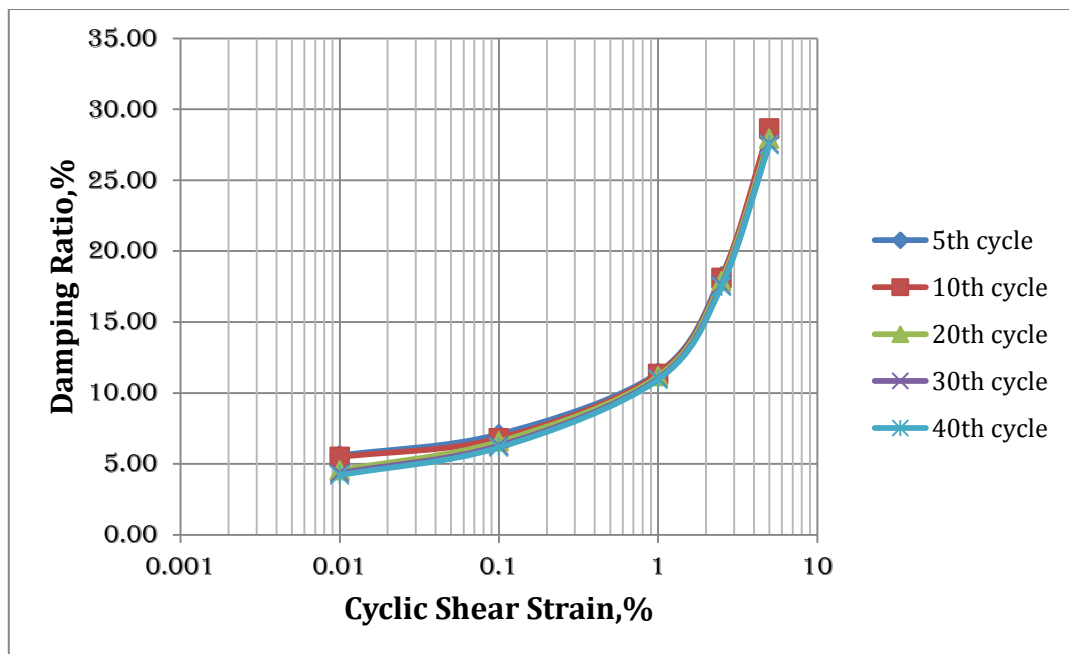


Figure 4.12: Variation of damping ratio with shear strain for different cycles for Test Pit 1 under axial stress of 200 kPa

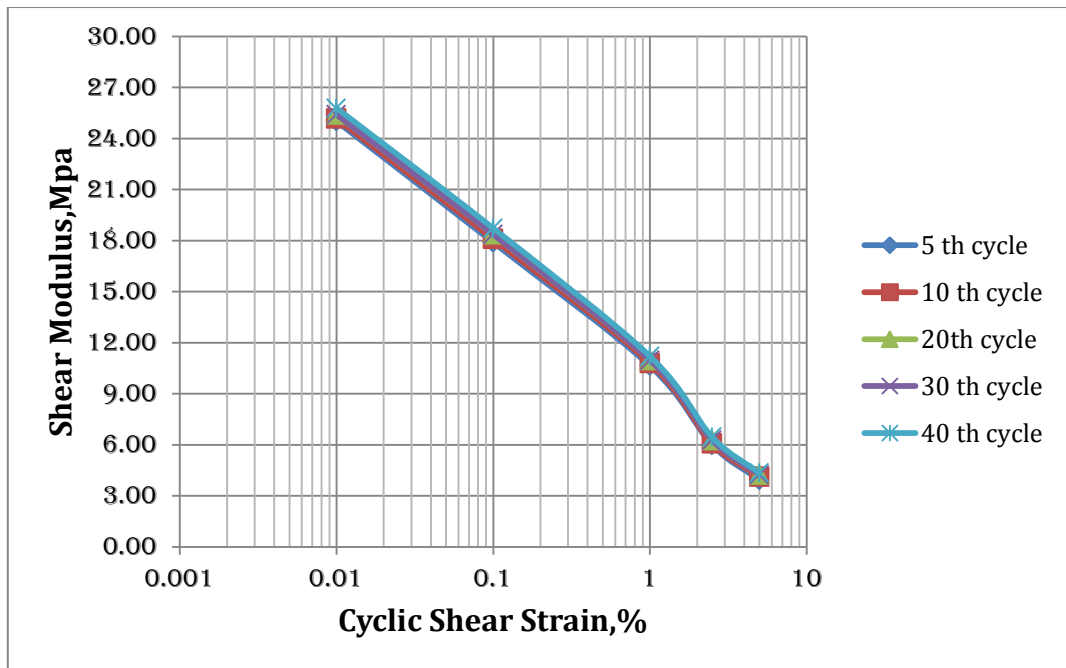


Figure 4.13: Variation of shear modulus with shear strain for different cycles for Test Pit 1 under axial stress of 400 kPa

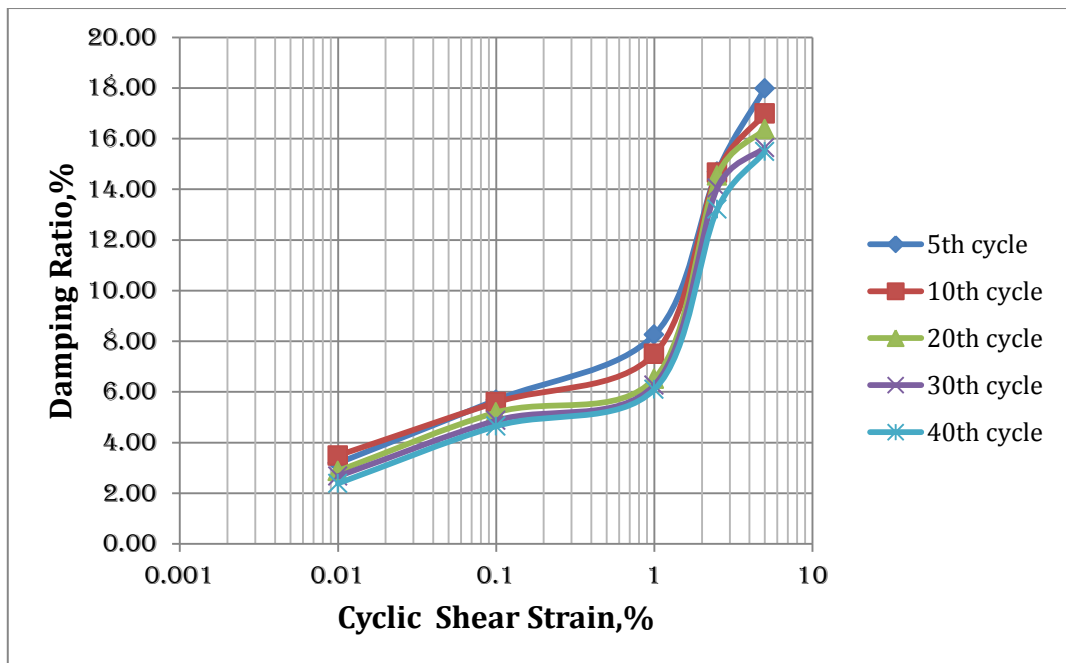


Figure 4.14: Variation of damping ratio with shear strain for different cycles for Test Pit 1 under axial stress of 400 kPa

### 4.3.2 Effect of number of cycles on shear modulus and damping ratio values

The number of cycles has noticeable effect on shear modulus and damping ratio values. The shear modulus increases and damping ratio decreases, with increasing number of cycles. However, this effect slowly fades out after the first 10 cycles. (See Figure 4.15 to 4.20)

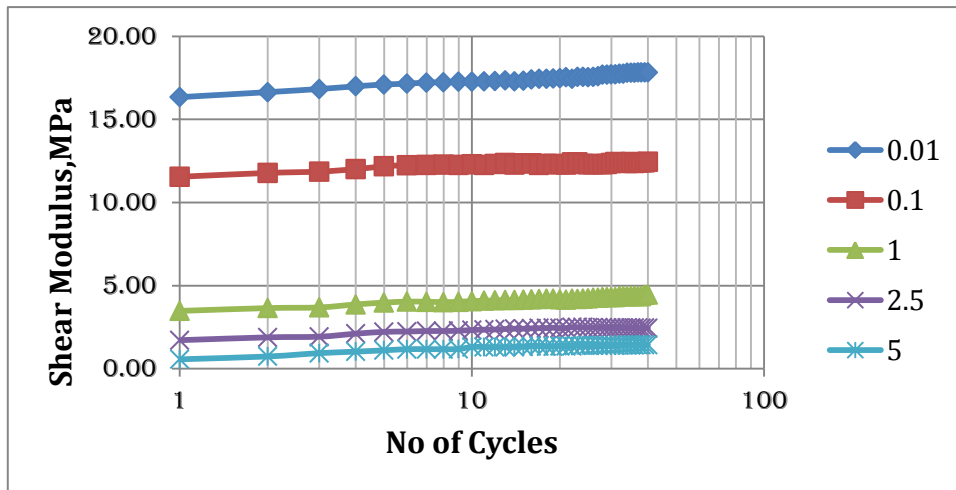


Figure 4.15: Effect of number of cycles on shear modulus values for Test Pit 1 under axial stress of 100 kPa

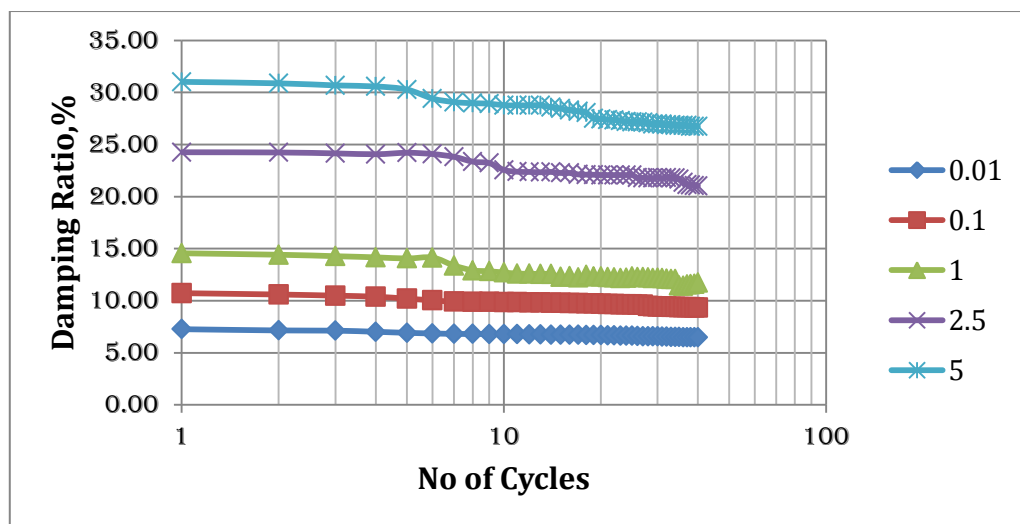


Figure 4.16: Effect of number of cycles on damping ratio values for Test Pit 1 under axial stress of 100 kPa

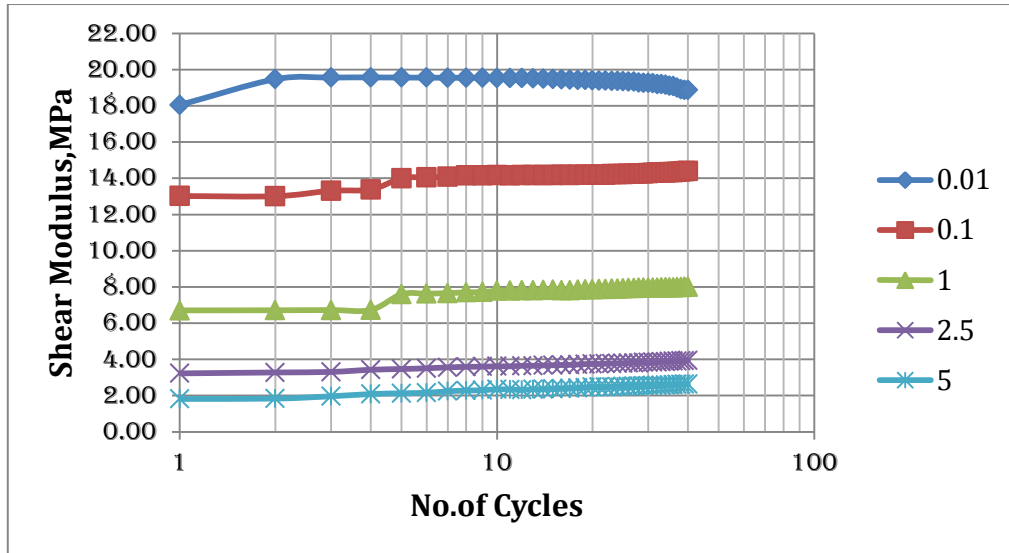


Figure 4.17: Effect of number of cycles on shear modulus values for Test Pit 1 under axial stress of 200 kPa

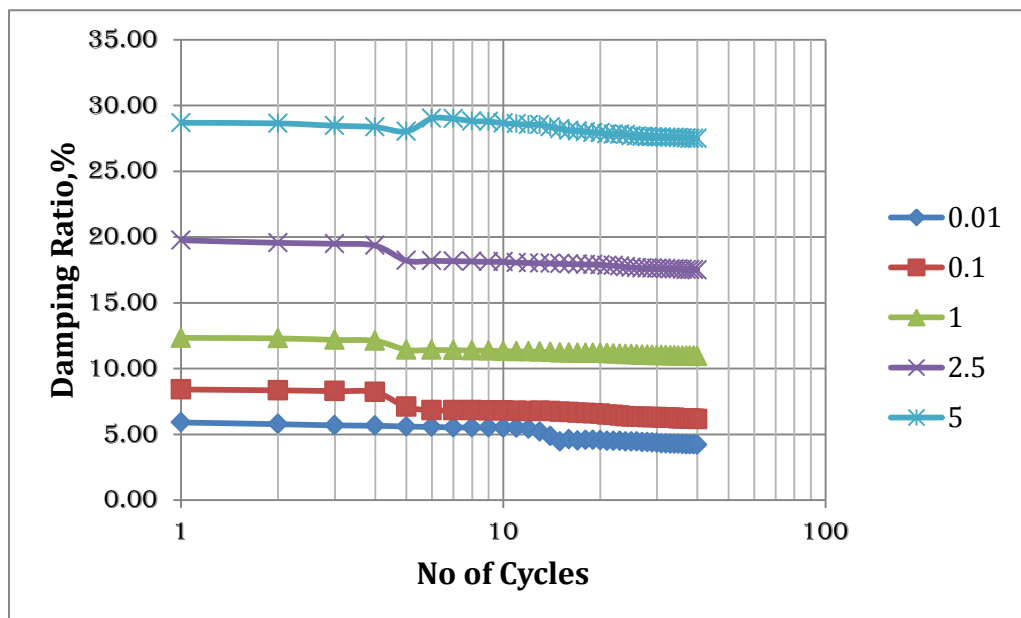


Figure 4.18: Effect of number of cycles on damping ratio values for Test Pit 1 under axial stress of 200 kPa

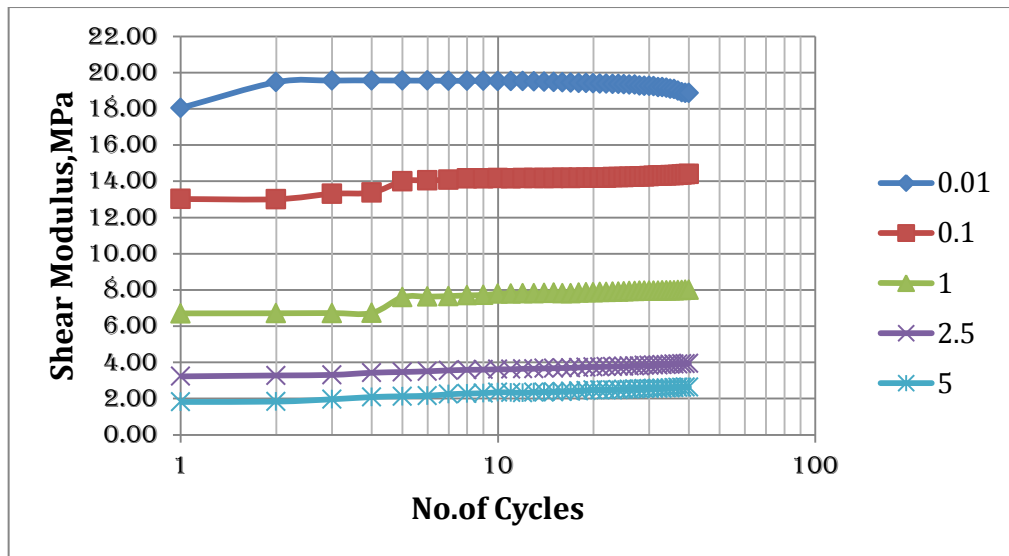


Figure 4.19: Effect of number of cycles on shear modulus values for Test Pit 1 under axial stress of 400 kPa

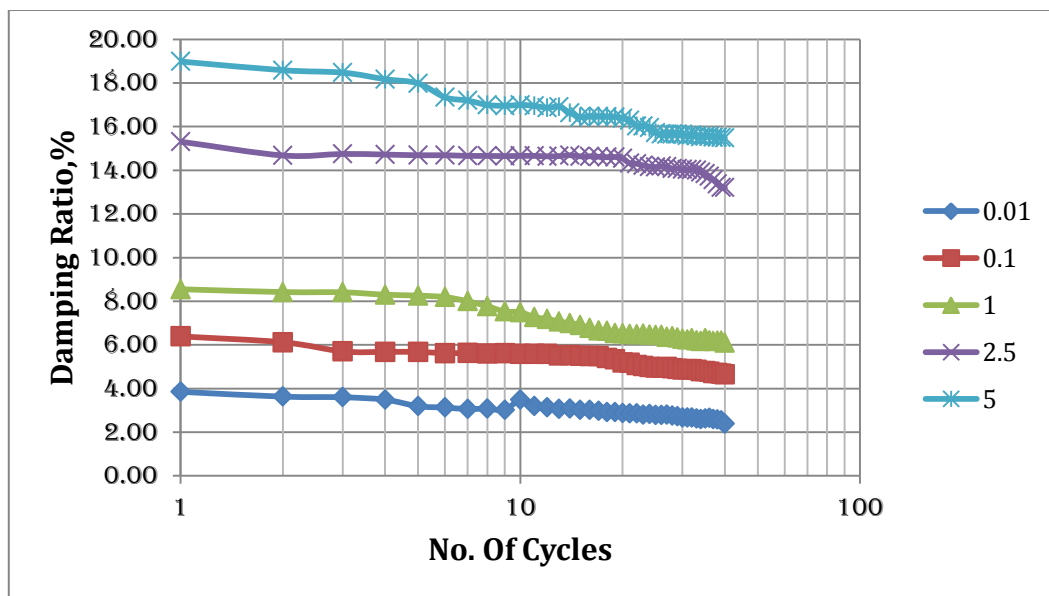


Figure 4.20: Effect of number of cycles on damping ratio values for Test Pit 1 under axial stress of 400 kPa

### 4.3.3 Influence of effective vertical stress on shear modulus and damping ratio values

Increment of effective vertical stress in soils causes a reduction in void ratio which in turn increases the shear modulus values. However, increase in effective vertical stress causes a decline in damping ratio magnitudes. The effect of varying confining pressure on shear modulus and damping ratio values for test pit 1 at 5<sup>th</sup> cycle is shown Figure 4.21 and 4.22 below.

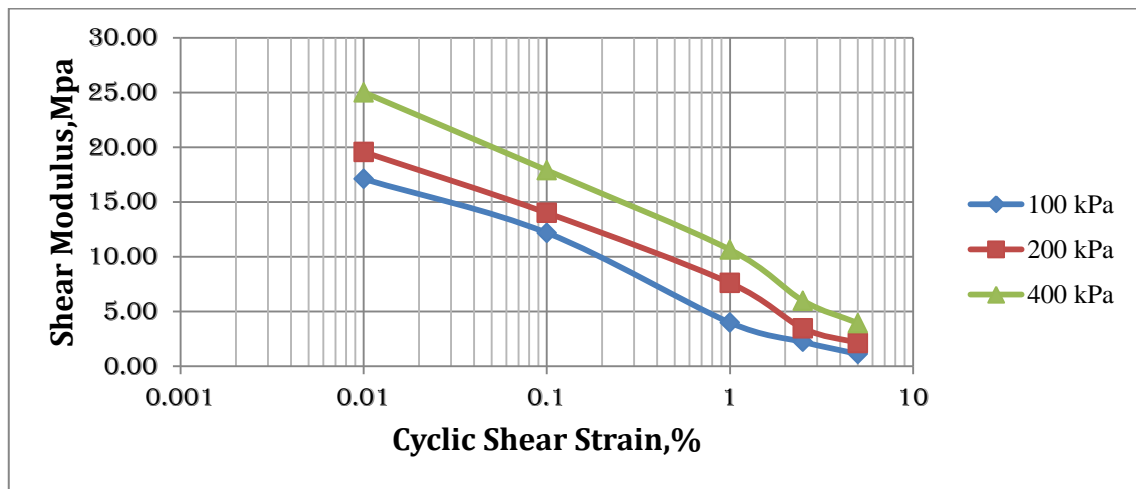


Figure 4.21: Effect of confining pressure on shear modulus values for Test Pit 1

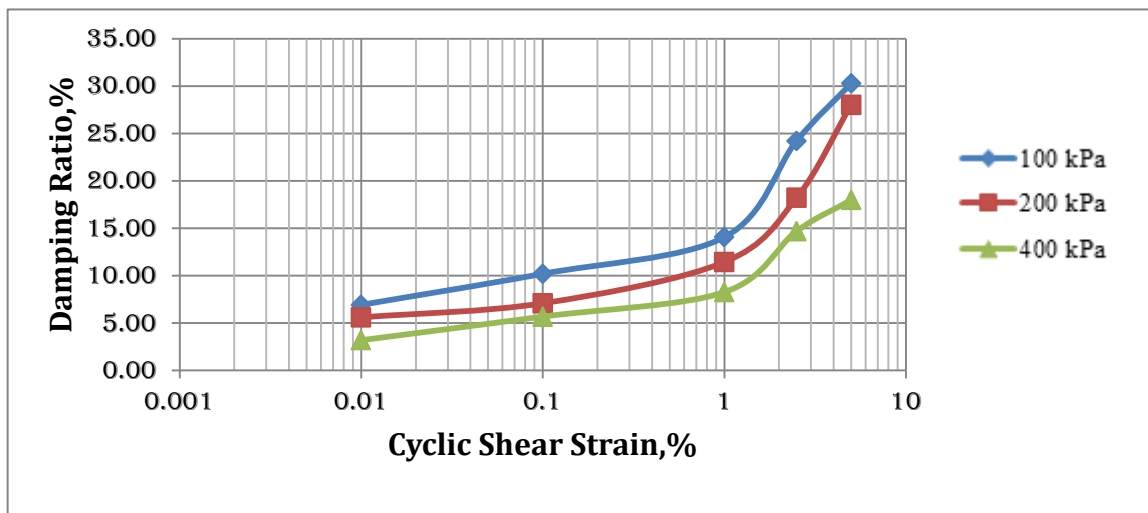


Figure 4.22: Effect of confining pressure on damping ratio values for Test Pit 1

As seen from Figure 4.23 and 4.24 below, at a given confining pressure, with increasing number of cycles shear modulus increase and damping ratio decrease.

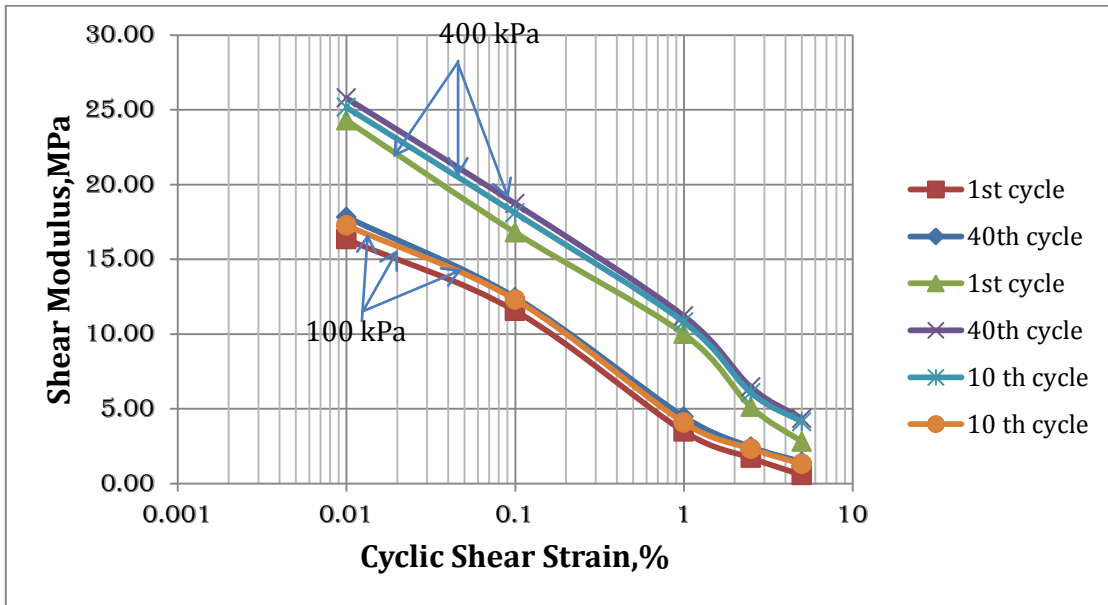


Figure 4.23: Effect of vertical stress on shear modulus values by varying vertical stress for Test Pit 1

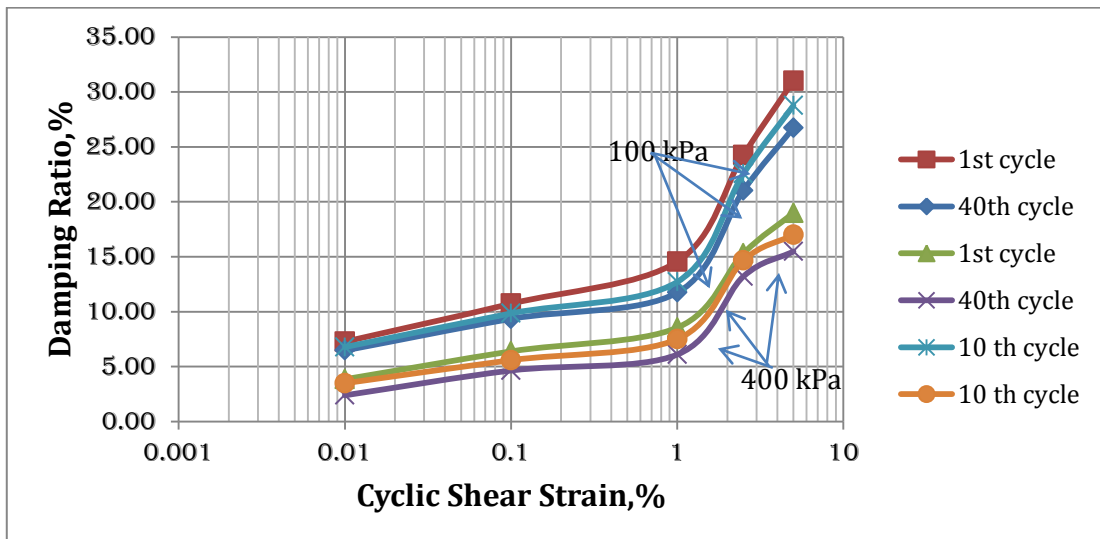


Figure 4.24: Effect of vertical stress on damping ratio values by varying vertical stress for Test Pit 1

#### 4.3.4 Estimation of maximum shear modulus

The shear modulus of soils at lower strains is important to determine the response in the linear elastic range. The shear modulus of soil at lower strain is known as maximum shear modulus. The value of maximum shear modulus,  $G_{max}$ , is dependent on plasticity, effective vertical stress, void ratio and stress history of the soil. The maximum shear modulus is usually normalized, and expressed as  $G/G_{max}$ .

The computation of the maximum (initial shear modulus) using Equation 2.4 is presented in Table 4.10 below.

Table 4.10: Estimation of maximum shear modulus

Parameter	Symbol			
Test pit 1				
Effective vertical stress	Po	100 kPa	200 kPa	400 kPa
Void ratio	e	1.08		
Plasticity index	PI	45		
Parameter depending on soil plasticity	a	0.325		
Over consolidation ratio	OCR	1.84	0.92	0.46
	$G_{max}$ (MPa)	55.381	62.523	70.586
Test pit 2				
Effective vertical stress	Po	100 kPa	200 kPa	400 kPa
Void ratio	e	0.97		
Plasticity index	PI	25		
Parameter depending on soil plasticity	a	0.21		
Over consolidation ratio	OCR	2.1	1.05	0.525
Maximum shear modulus	$G_{max}$ (MPa)	62.751	76.722	93.803
Test pit 6				
Effective vertical stress	Po	100 kPa	200 kPa	400 kPa
Void ratio	e	0.95		
Plasticity index	PI	42		
Parameter depending on soil plasticity	a	0.311		
Over consolidation ratio	OCR	2.1	1.05	0.525
Maximum shear modulus	$G_{max}$ (MPa)	69.699	79.455	90.576
Test pit 4				
Effective vertical stress	Po	100 kPa	200 kPa	400 kPa
Void ratio	e	1.11		
Plasticity index	PI	23		
Parameter depending on soil plasticity	a	0.198		
Over consolidation ratio	OCR	1.84	0.92	0.46

Maximum shear modulus	$G_{max}(MPa)$	48.396	60.332	74.381
Test pit 7				
Effective vertical stress	Po	100 kPa	200 kPa	400 kPa
Void ratio	e	1.032		
Plasticity index	PI	33		
Parameter depending on soil plasticity	a	0.258		
Over consolidation ratio	OCR	1.84	0.92	0.46
Maximum shear modulus	$G_{max}(MPa)$	57.215	67.664	80.021
Cont.....				
Test pit 8				
Effective vertical stress	Po	100 kPa	200 kPa	400 kPa
Void ratio	e	0.96		
Plasticity index	PI	40		
Parameter depending on soil plasticity	a	0.30		
Over consolidation ratio	OCR	2.1	1.05	0.525
Maximum shear modulus	$G_{max}(MPa)$	68.101	78.228	89.861

Summary of the normalized shear modulus values ( $G / G_{\max}$ ) for all test pits under axial stress of 100 kPa, 200 kPa and 400 kPa is presented in Table 4.11

Table 4.11: Normalized modulus values for all test pits

	$G / G_{\max}$				
Strain level	0.01	0.1	1	2.5	5
Effective vertical stress 100 kPa					
Test pit 1	0.310	0.220	0.07	0.04	0.02
Test pit 2	0.220	0.136	0.0412	0.020	0.010
Test pit 4	0.283	0.183	0.0419	0.020	0.0104
Test pit 6	0.275	0.201	0.086	0.061	0.046
Test pit 7	0.281	0.182	0.051	0.024	0.010
Test pit 8	0.272	0.183	0.070	0.055	0.039
Effective vertical stress 200 kPa					
Test pit 1	0.314	0.227	0.12	0.06	0.03
Test pit 2	0.212	0.131	0.070	0.025	0.0140
Test pit 4	0.267	0.166	0.0702	0.0258	0.0147
Test pit 6	0.267	0.203	0.122	0.070	0.053
Test pit 7	0.276	0.171	0.090	0.032	0.015
Test pit 8	0.260	0.188	0.108	0.053	0.035
Effective vertical stress 400 kPa					
Test pit 1	0.35	0.25	0.15	0.08	0.06
Test pit 2	0.217	0.151	0.1131	0.0701	0.0292
Test pit 4	0.272	0.189	0.1137	0.0708	0.0293
Test pit 6	0.298	0.220	0.139	0.088	0.066
Test pit 7	0.293	0.204	0.151	0.091	0.033
Test pit 8	0.296	0.217	0.136	0.084	0.062

#### 4.3.5 Effect of plasticity on shear modulus and damping ratio values

Shear modulus and damping ratio for coarse grained soils can be represented by average values. Unlike coarse grained soils, shear modulus and damping values of fine grained soils show much scatter and must be determined on a site specific basis. Of many factors plasticity of the soil is the paramount factor which affects G and D values of the cohesive soils. As seen from Figures 4.2.5 to 4.2.8 below, the shear modulus increases and damping ratio decreases significantly with increasing plasticity index of soils. It is also observed that the soils have lower shear modulus at higher strains. Hence the effect of plasticity on shear modulus is less significant for strains greater than 1 %.

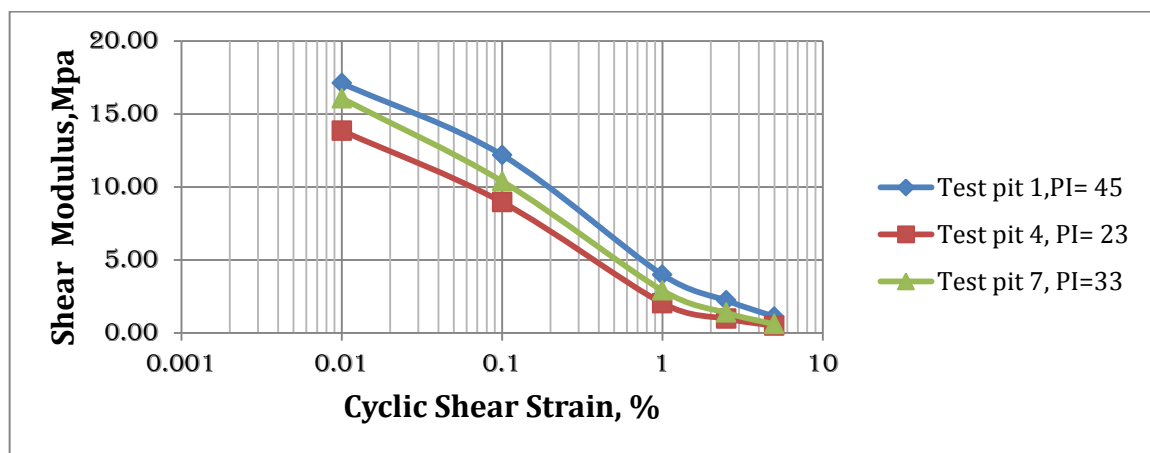


Figure 4.25: Influence of plasticity on shear modulus values (TP1, TP4 and TP7) under axial stress of 100 kPa

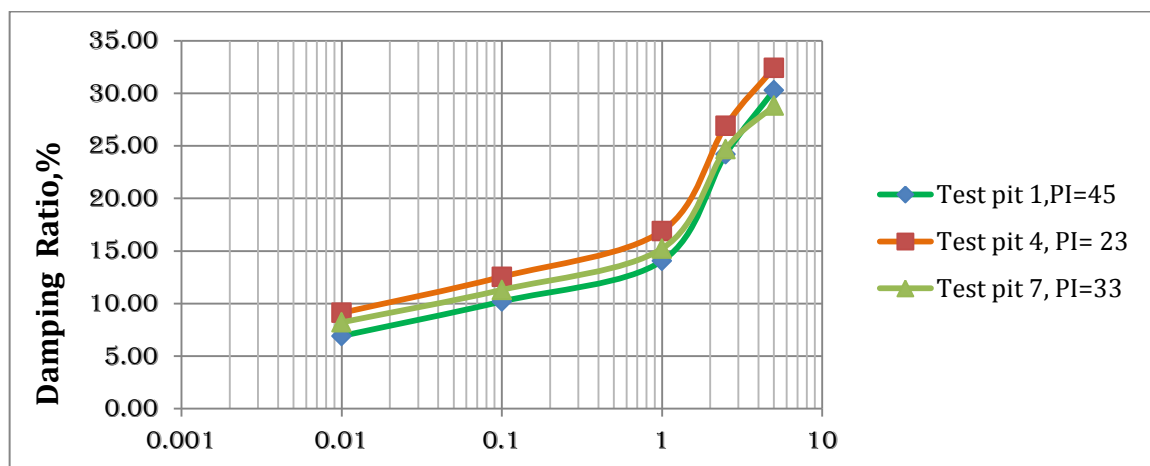


Figure 4.26: Influence of plasticity on damping ratio values (TP1, TP4 and TP7) under axial stress of 100 kPa

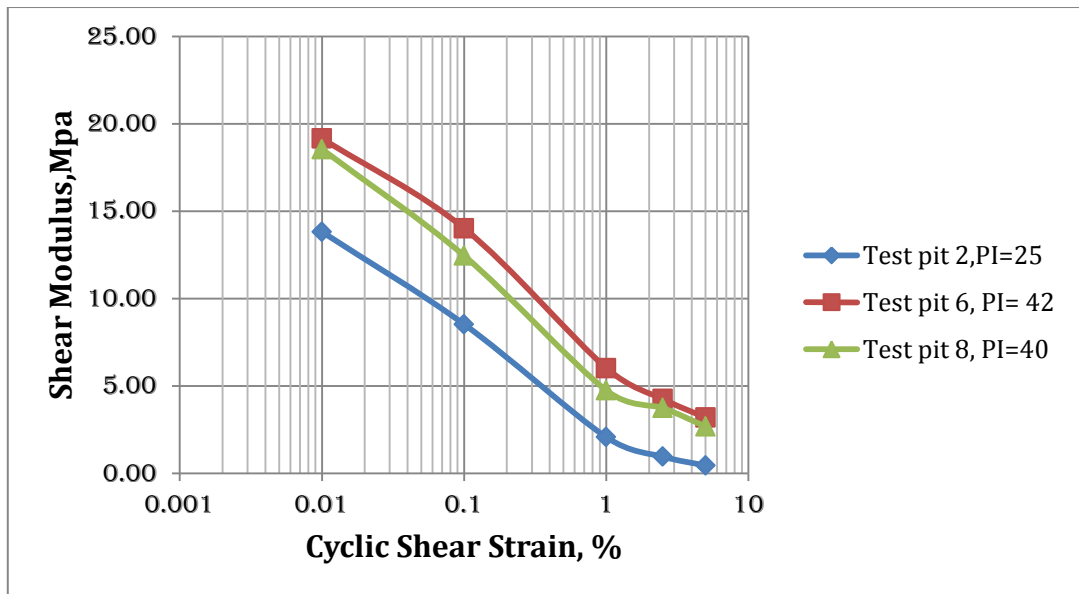


Figure 4.27: Influence of plasticity on shear modulus values (TP2, TP 6 and TP8) under axial stress of 100 kPa

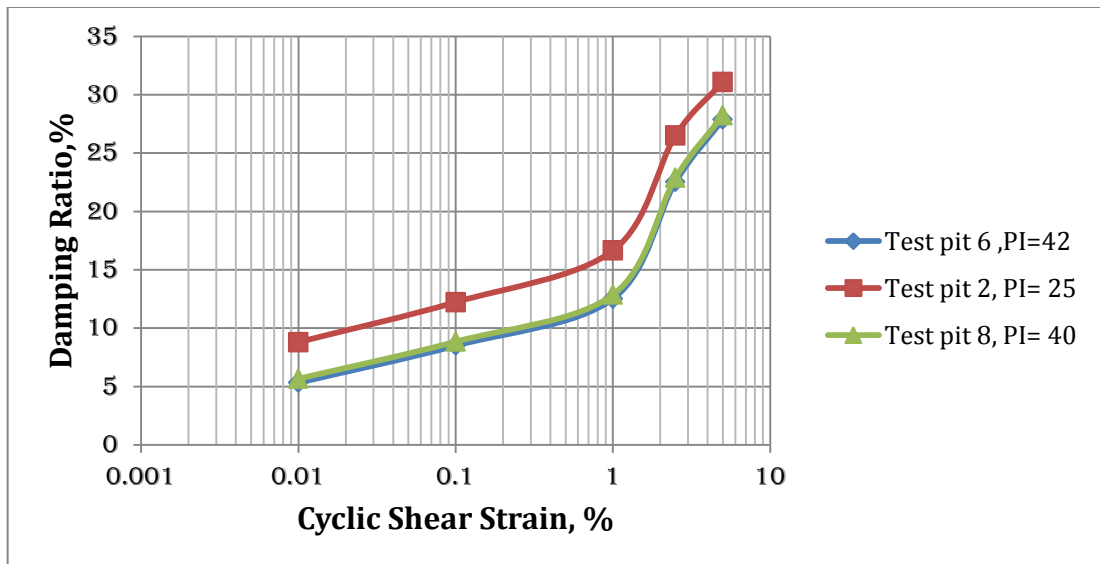


Figure 4.28: Influence of plasticity on damping ratio values (TP 2, TP 6 and TP 8) under axial stress of 100 kPa

The following Figures 4.29 and 4.30 shows all in one plots of shear modulus and damping ratio of all test pits. It is observed that increase in value of shear modulus and decrease in damping potential of all test pits with an increasing plasticity index of soils.

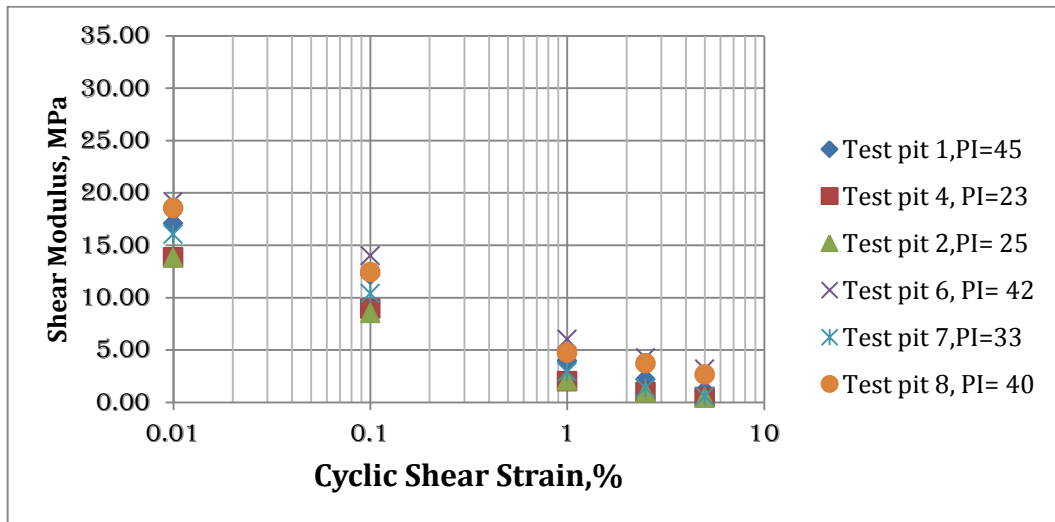


Figure 4.29: Influence of plasticity on shear modulus values (TP 1, TP2, TP4, TP6, TP7, and TP8) under axial stress of 100 kPa

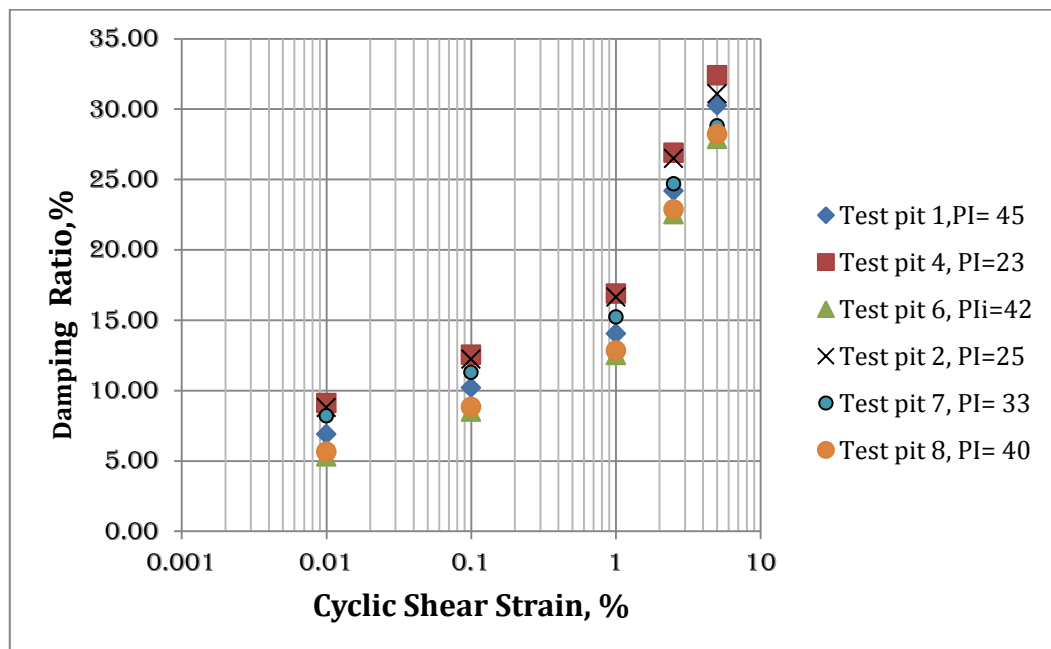


Figure 4.30: Influence of plasticity on damping ratio values (TP 1, TP2, TP4, TP6, TP7, and TP8) under axial stress of 100 kPa

## CHAPTER FIVE

### 5 Comparison of Test Results with Previous Studies

#### 5.1 Introduction

The results of experimental values are compared with previously published literature data. Modulus reduction and damping ratio curves of saturated clay and sand have been previously developed by Seed and Idriss (1970). Modulus reduction and damping ratio curves for local clay soil have been developed by Dimer (2013). Modulus reduction and damping ratio curves for silty soils had been developed by Mengistu (2014) and Gemechu (2011).

#### 5.2 Shear modulus reduction

Comparison of normalized shear results were made with published literature data (Seed and Idriss, 1970; Vucetic and Dobry, 1991; Dimer, 2013; Gemechu, 2011; Mengistu, 2014).

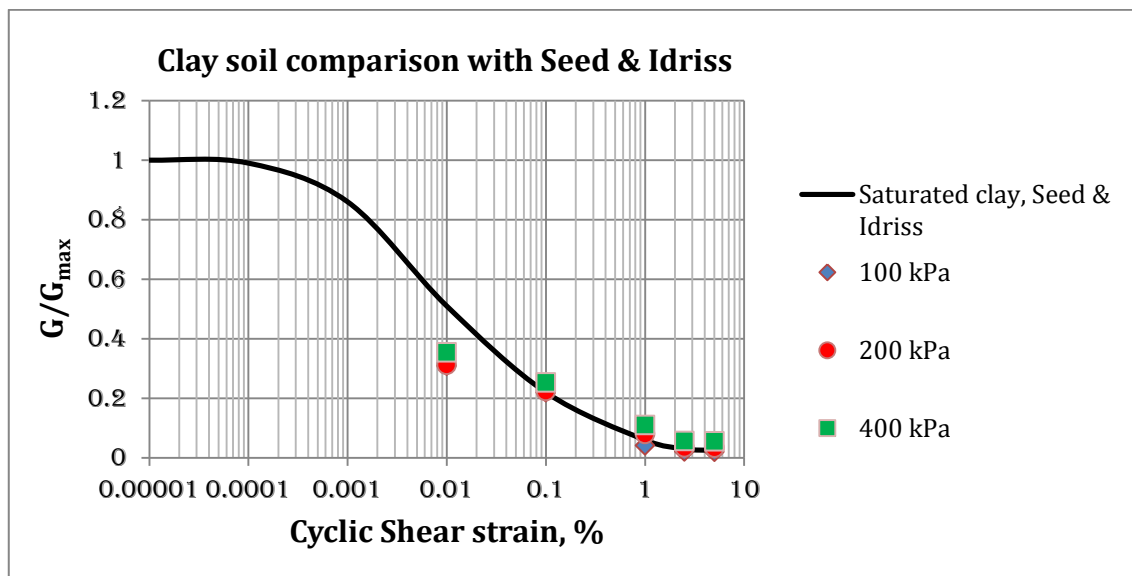


Figure 5.1: Comparison of modulus reduction values of clay soil (PI=45) with curves developed for saturated clay by Seed and Idriss (1970)

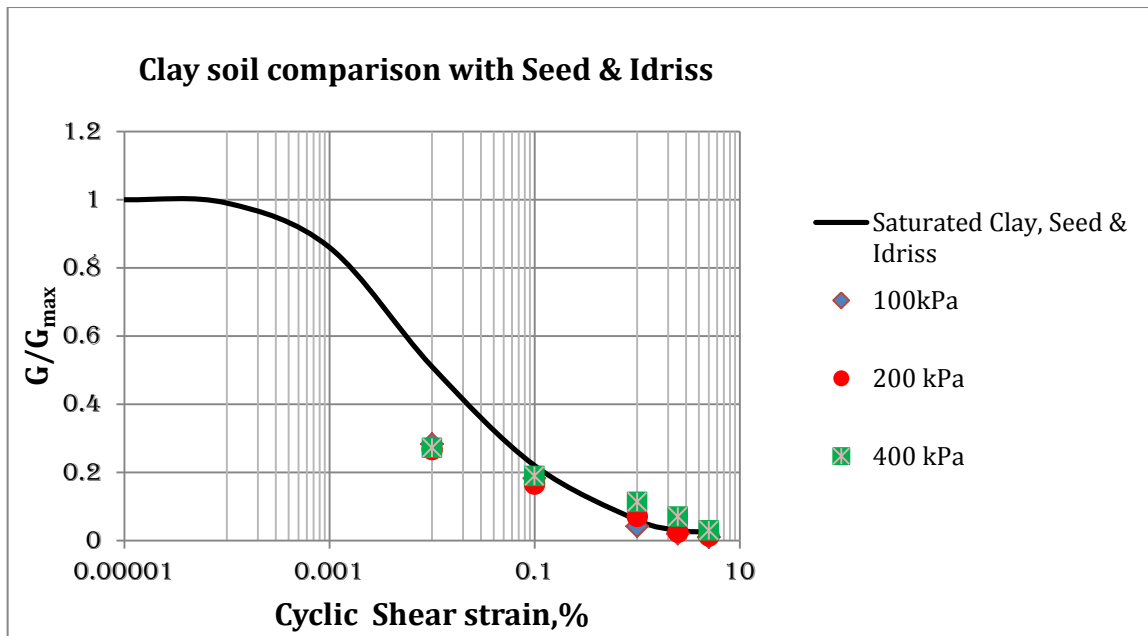


Figure 5.2: Comparison of modulus reduction values of clay soil (PI=23) with curves developed for saturated clay by Seed and Idriss (1970)

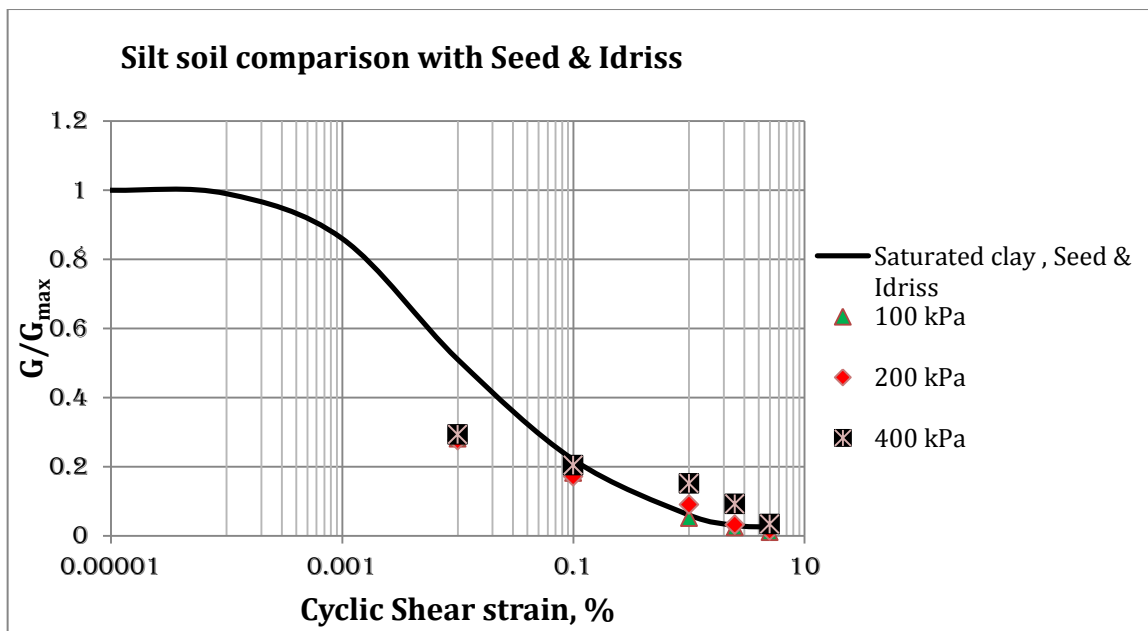


Figure 5.3: Comparison of modulus reduction values of silt soil (PI=33) with curves developed for saturated clay by Seed and Idriss (1970)

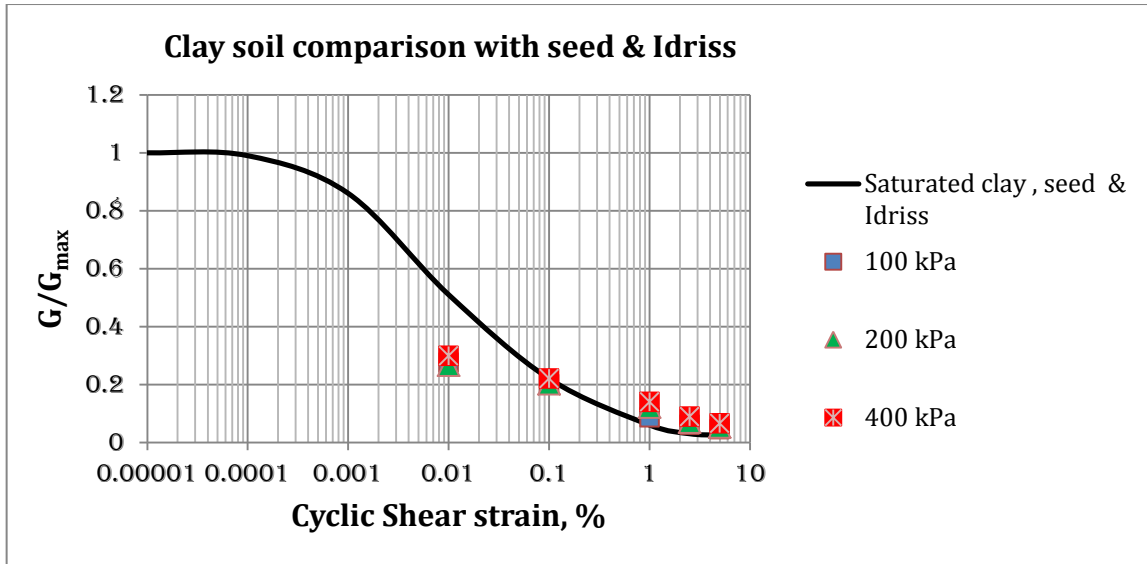


Figure 5.4: Comparison of modulus reduction values of clay soil (PI=42) with curves developed for saturated clay by Seed and Idriss (1970)

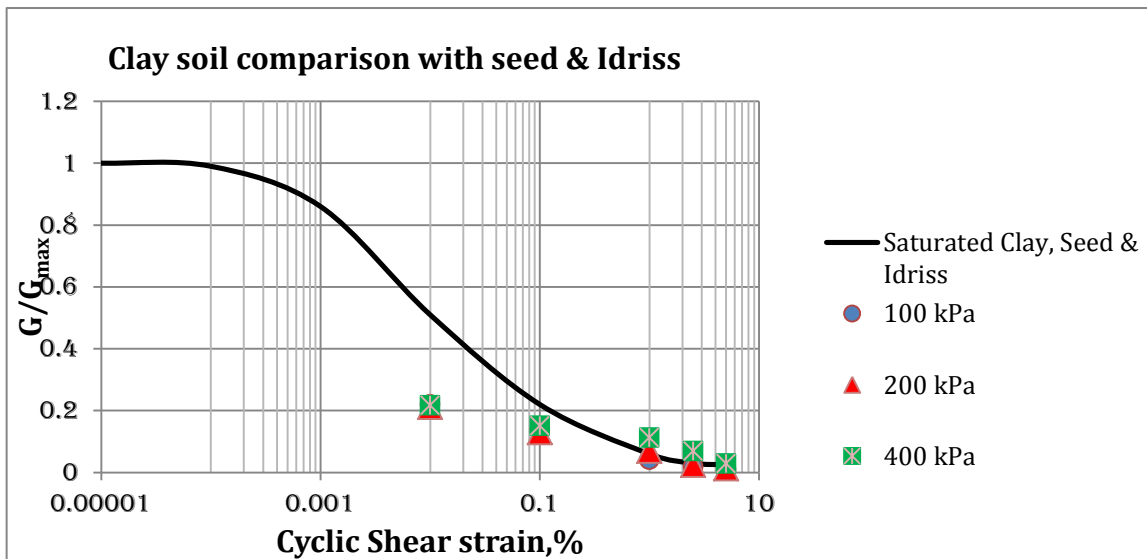


Figure 5.5: Comparison of modulus reduction values of clay soil (PI=25) with curves developed for saturated clay by Seed and Idriss (1970)

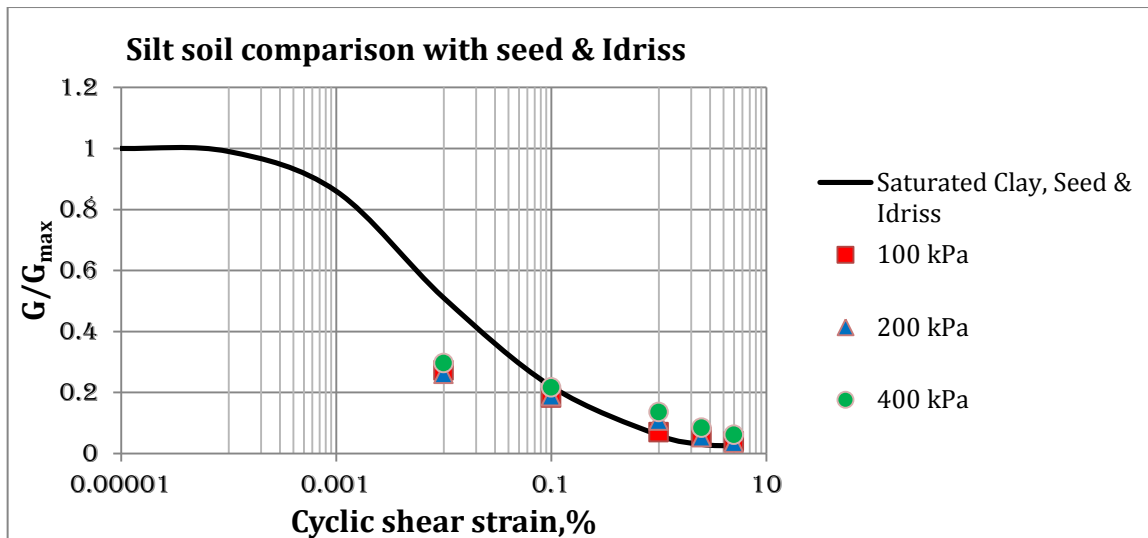


Figure 5.6: Comparison of modulus reduction values of silt soil (PI=40) with curves developed for saturated clay by Seed and Idriss (1970)

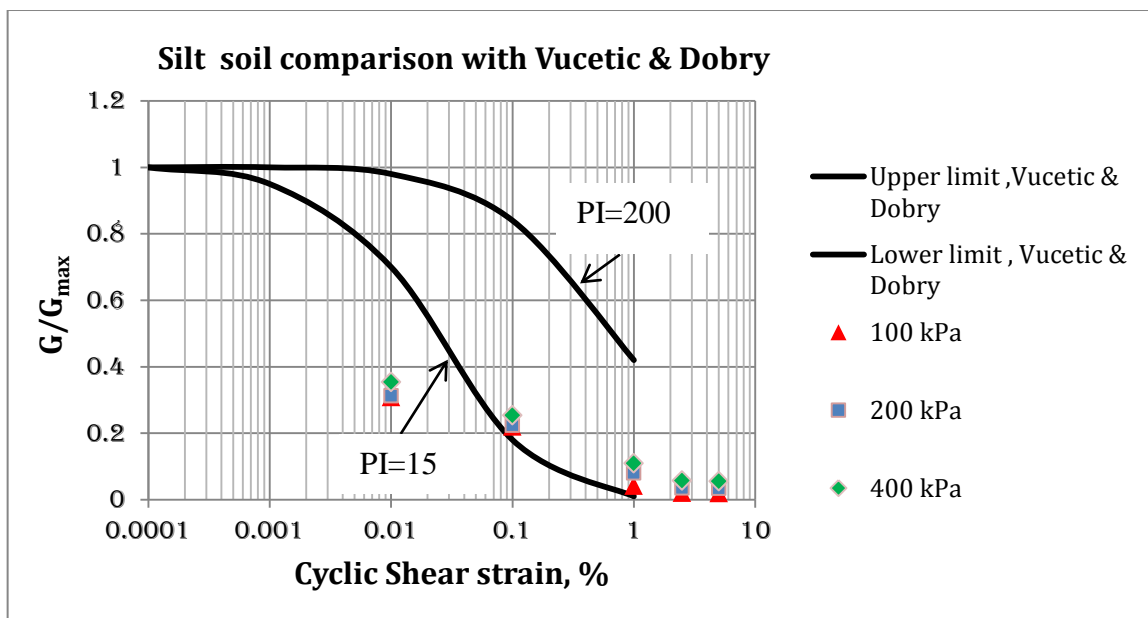


Figure 5.7: Comparison of modulus reduction values of silt soil with curves developed for plastic soils by Vucetic and Dobry (1991)

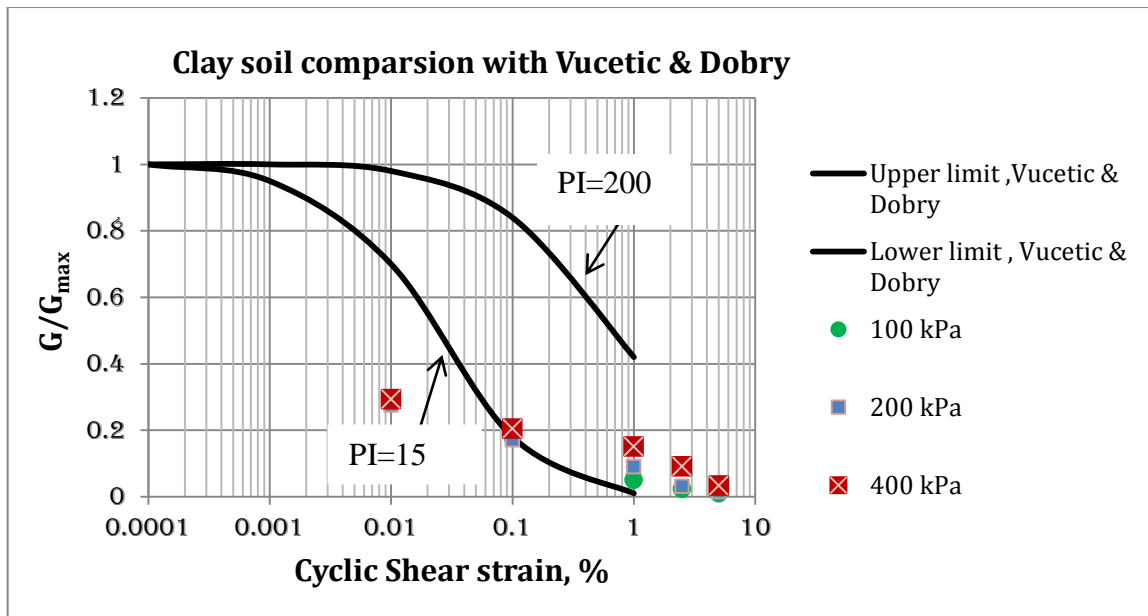


Figure 5.8: Comparison of modulus reduction values of clay soil with curves developed for plastic soils by Vucetic and Dobry (1991)

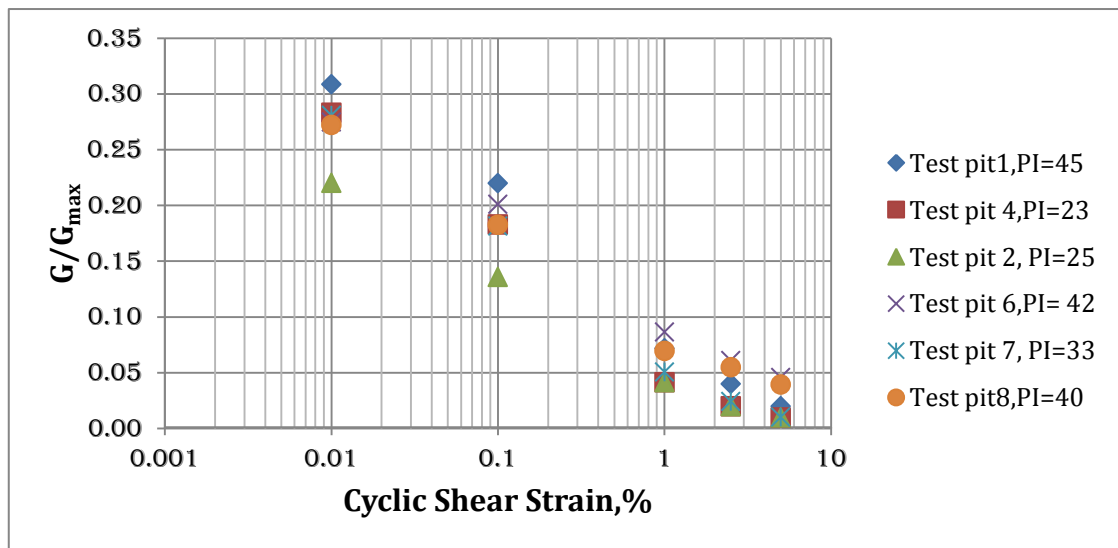


Figure 5.9: Modulus reduction values of all Test Pits

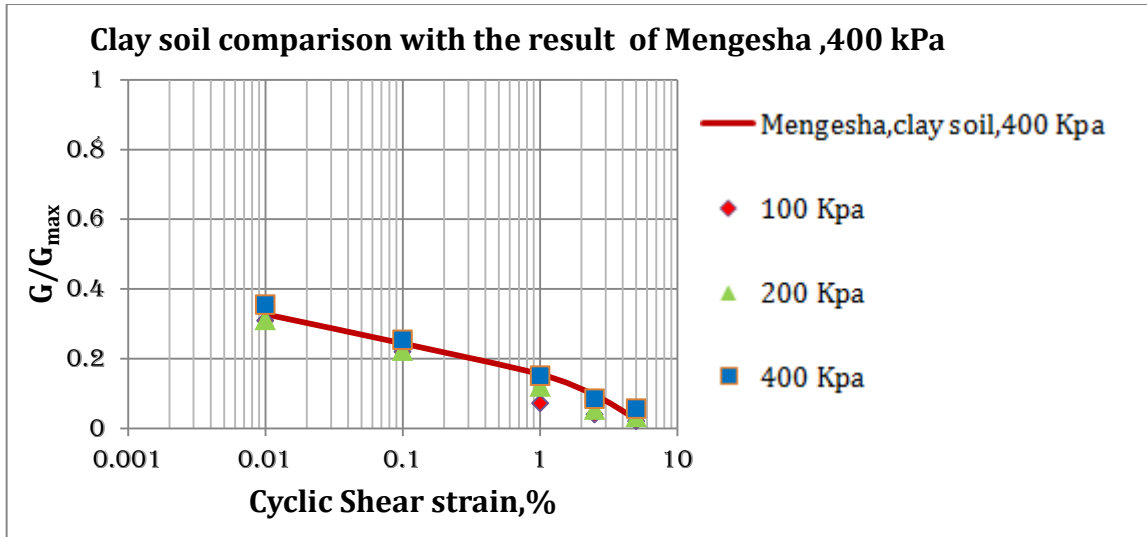


Figure 5.10: Comparison of modulus reduction values of clay soil with curves developed for clay soils by Dimer (2013)

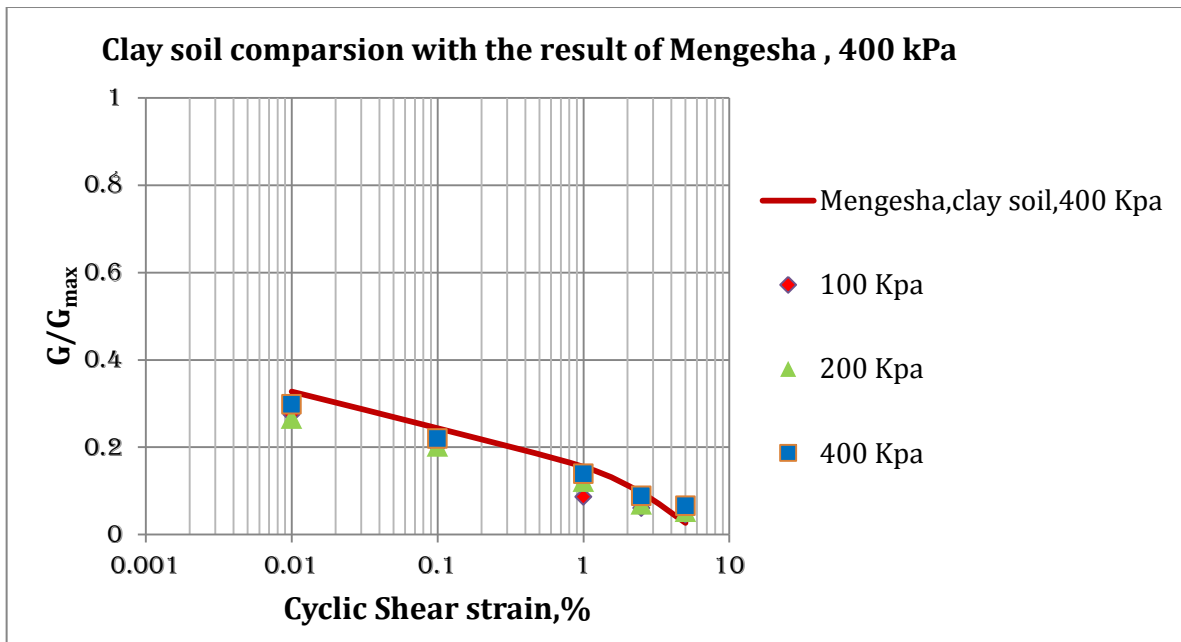


Figure 5.11: Comparison of modulus reduction values of clay soil with curves developed for clay soils by Dimer (2013)

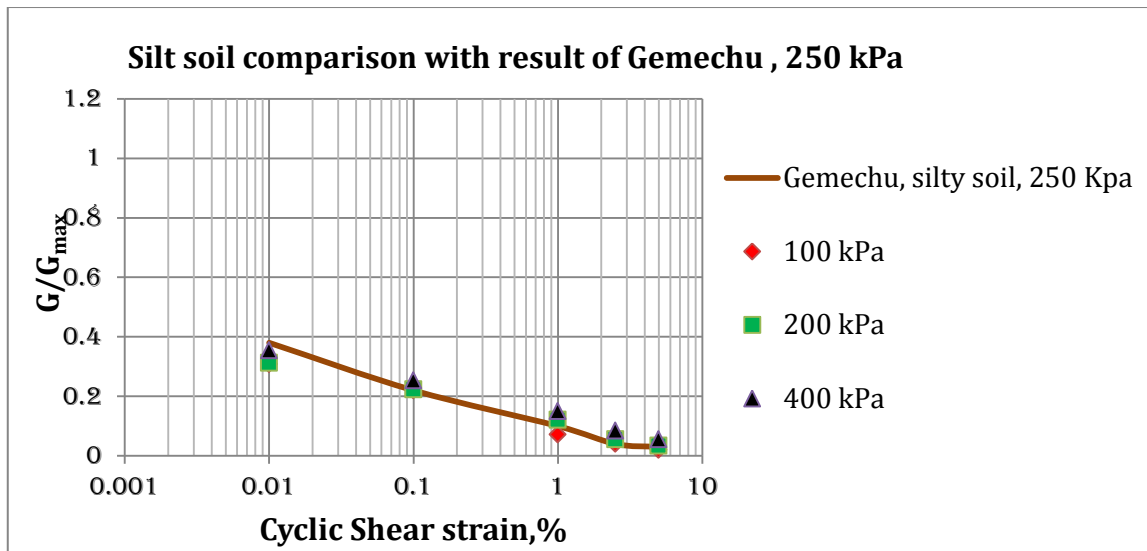


Figure 5.12: Comparison of modulus reduction values of silty soil with curves developed for silt soils by Gemechu (2011)

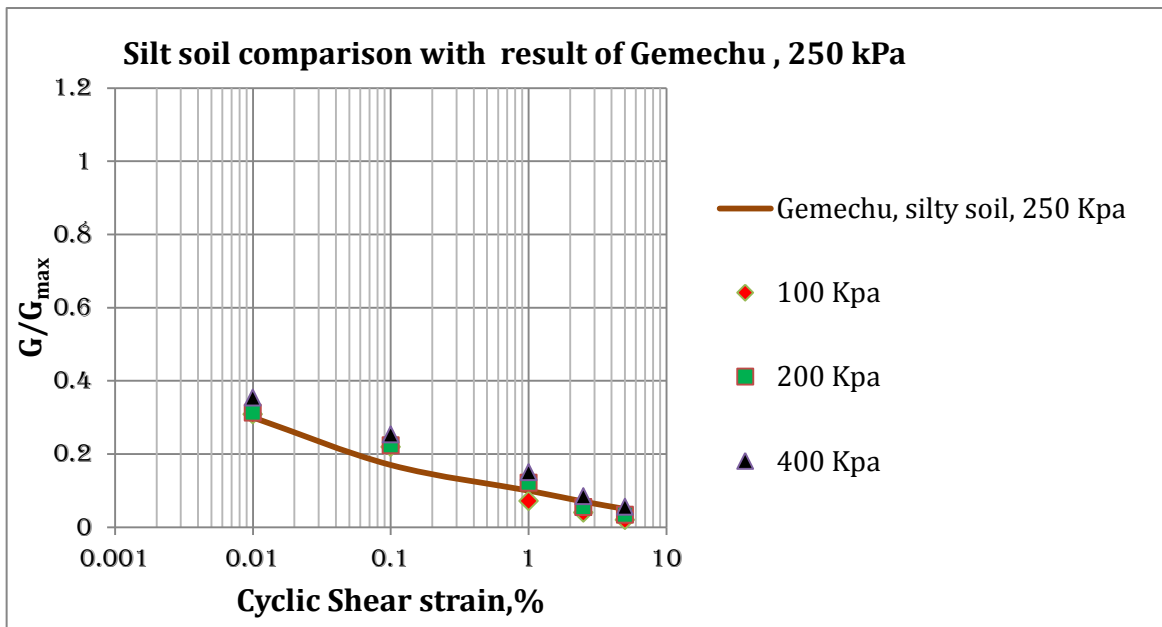


Figure 5.13: Comparison of modulus reduction values of silt soil with curves developed for silty soils by Gemechu (2011)

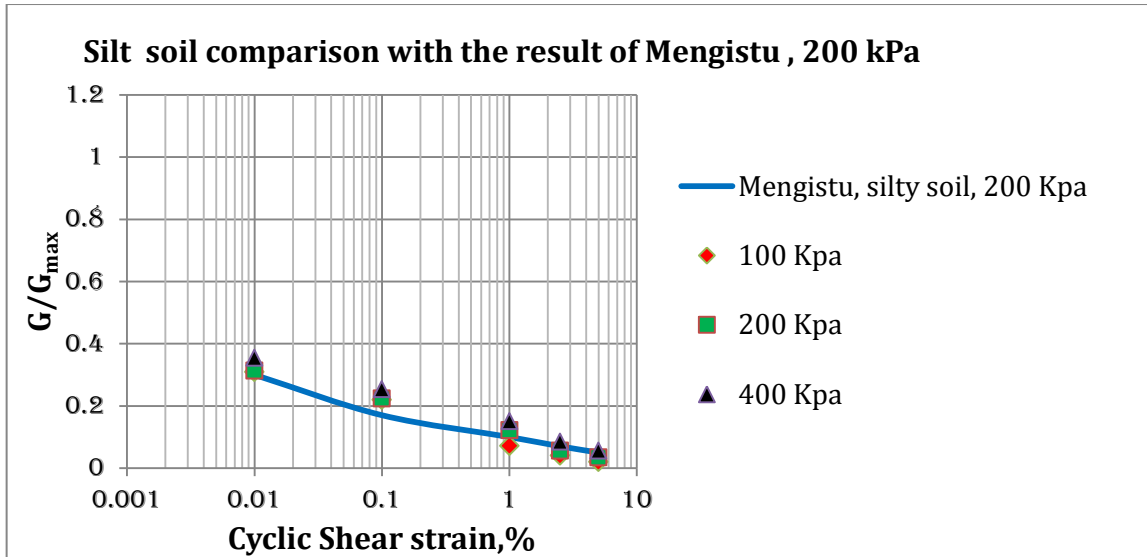


Figure 5.14: Comparison of modulus reduction values of silt soil with curves developed for silt soils by Mengistu (2014)

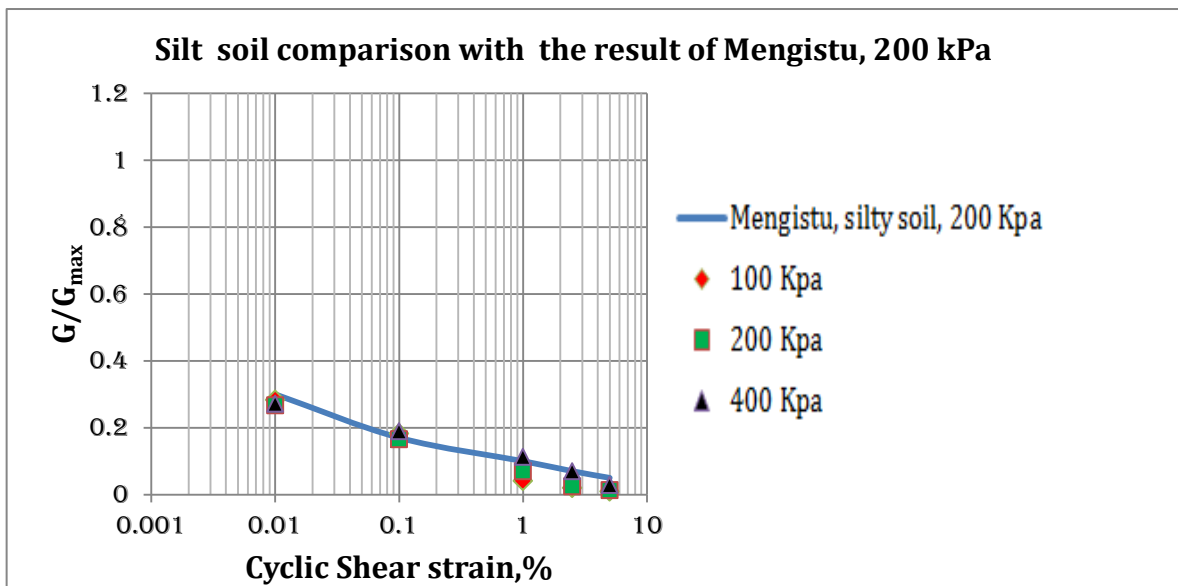


Figure 5.15: Comparison of modulus reduction values of silt soil with curves developed for silt soils by Mengistu (2014)

## **Discussion**

As seen from Figure 5.1 to 5.8, the computed shear modulus reduction values at lower strains (i.e. less than 0.01 %) are lower than the curves developed for saturated clays by Seed and Idriss (1970) and Vucetic and Dobry (1991). This reduction in value at strain less than 0.01 % could be due to sample preparation and testing condition. Conversely, the modulus reduction values at higher strains agree with the curves developed by Seed and Idriss (1970) and Vucetic and Dobry (1991).

Comparisons were also made with local silt and clay soils of Arbaminch, Adama and Ziway having plasticity index (18 to 49), for effective vertical stress (100 kPa to 400 kPa) and preconsolidation pressure of (60 kPa to 198 kPa).

Figure 5.10 to 5.15 show comparison of normalized modulus reduction values with local soils. It is observed from Figure 5.15 that, the modulus reduction values show slight scatter with the curves developed by Mengistu (2014) for silty soils but compatible with the curves developed by Gemechu (2011) and Dimer (2013) for silty soils of Adama and for clay soils of Arbaminch, respectively.

### 5.3 Damping ratio

Comparison of damping ratio results is made with previous literature data (Seed and Idriss, 1970; Dimer, 2013). Figure 5.16 to 5.21 shows that for confining stress of 100 and 200 kPa the damping ratio values of tested soils are within the curves provided by Seed and Idriss (1970) for saturated clays. However, for confining stress of 400 kPa the damping values of the tested soils are mostly outside the limits. Comparisons were also made with local clay soils. As seen in Figure 5.22 the damping values are slightly higher than the one provided by Dimer (2013) for clay soils.

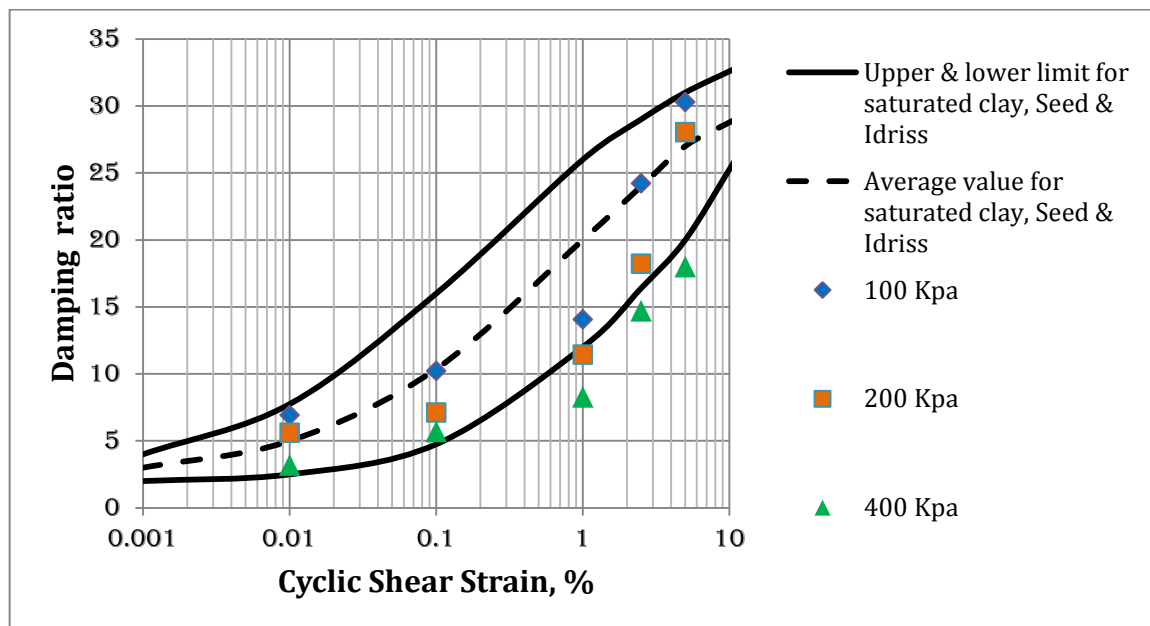


Figure 5.16: Comparison of damping ratio values of clay soil (PI=45) with curves developed for Saturated clay by Seed and Idriss (1970)

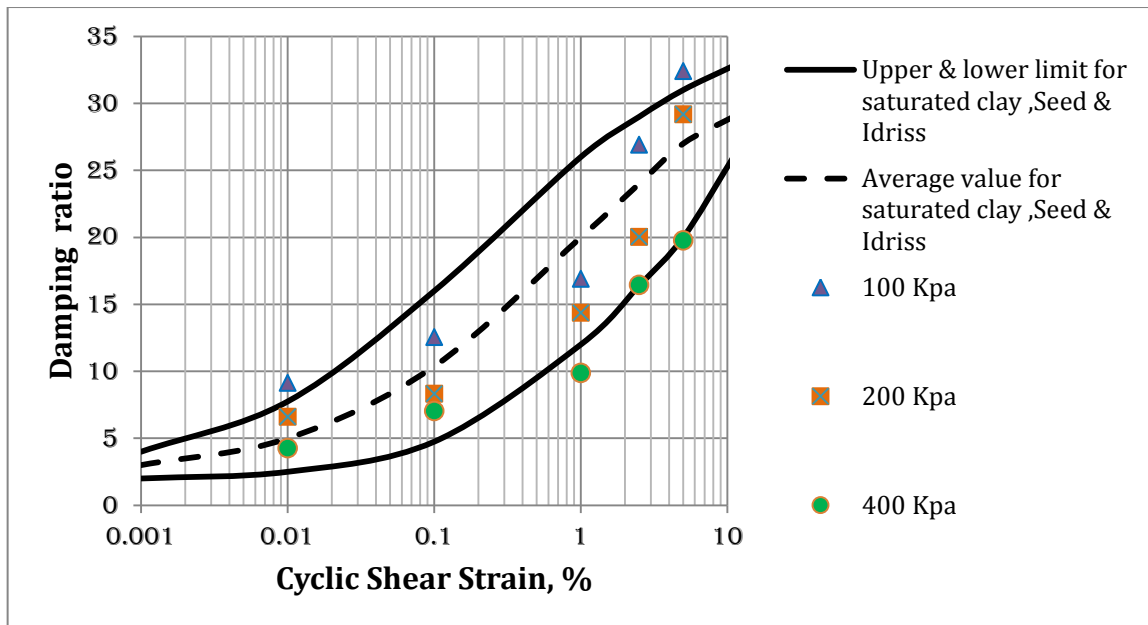


Figure 5.17: Comparison of damping ratio values of clay soil (PI=23) with curves developed for Saturated clay by Seed and Idriss (1970)

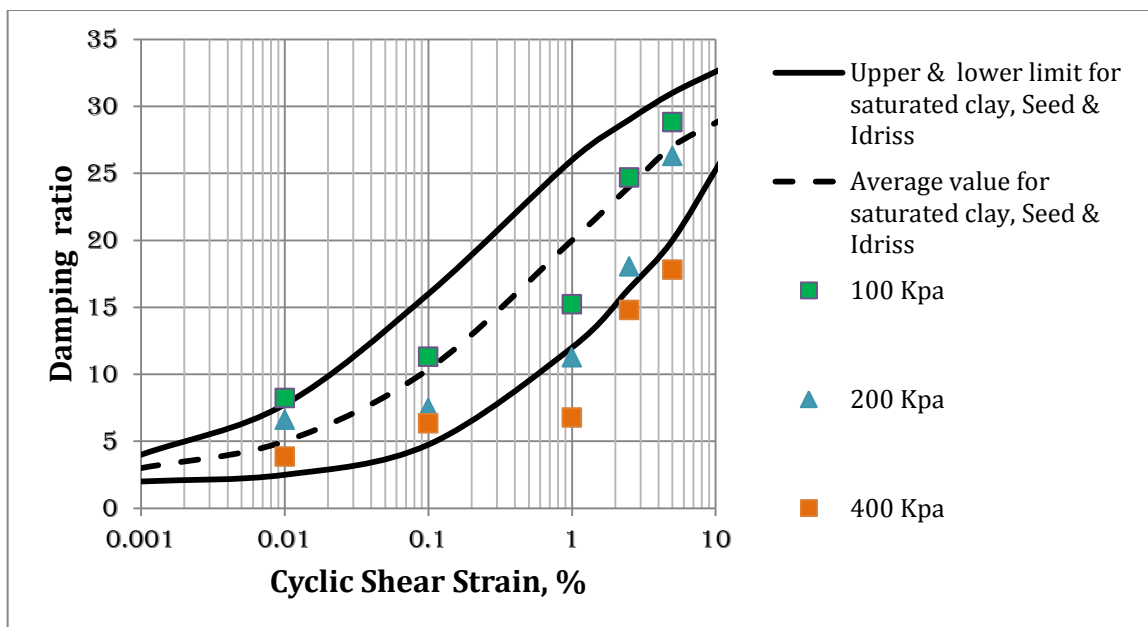


Figure 5.18: Comparison of damping ratio values of silty soil (PI=33) with curves developed for Saturated clay by Seed and Idriss (1970).

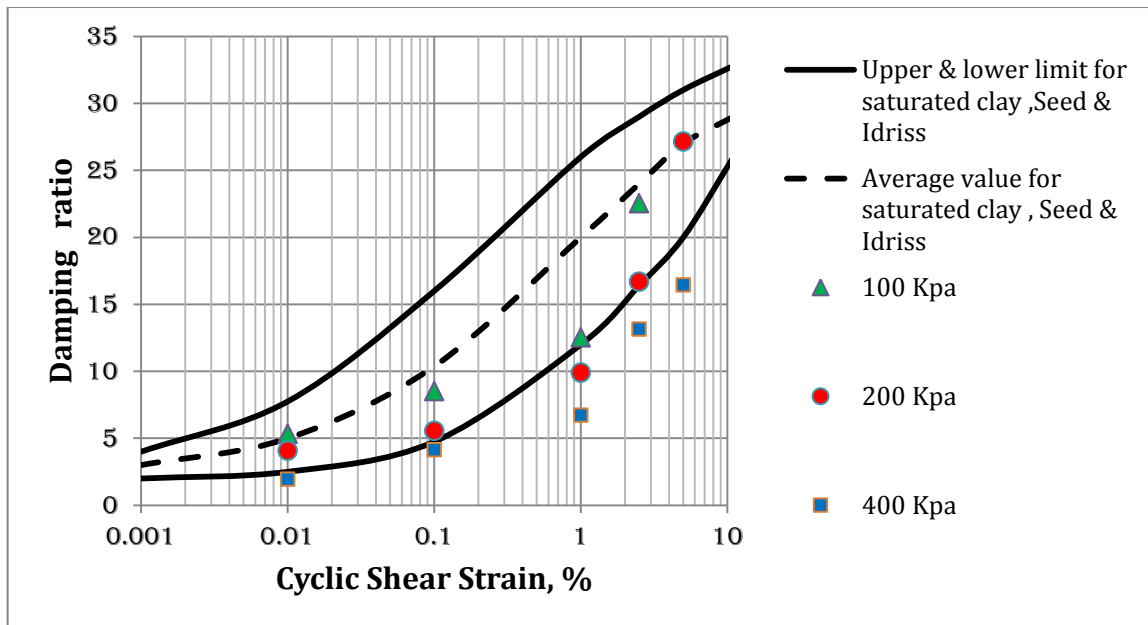


Figure 5.19: Comparison of damping ratio values of clay soil (PI=42) with curves developed for Saturated clay by Seed and Idriss (1970)

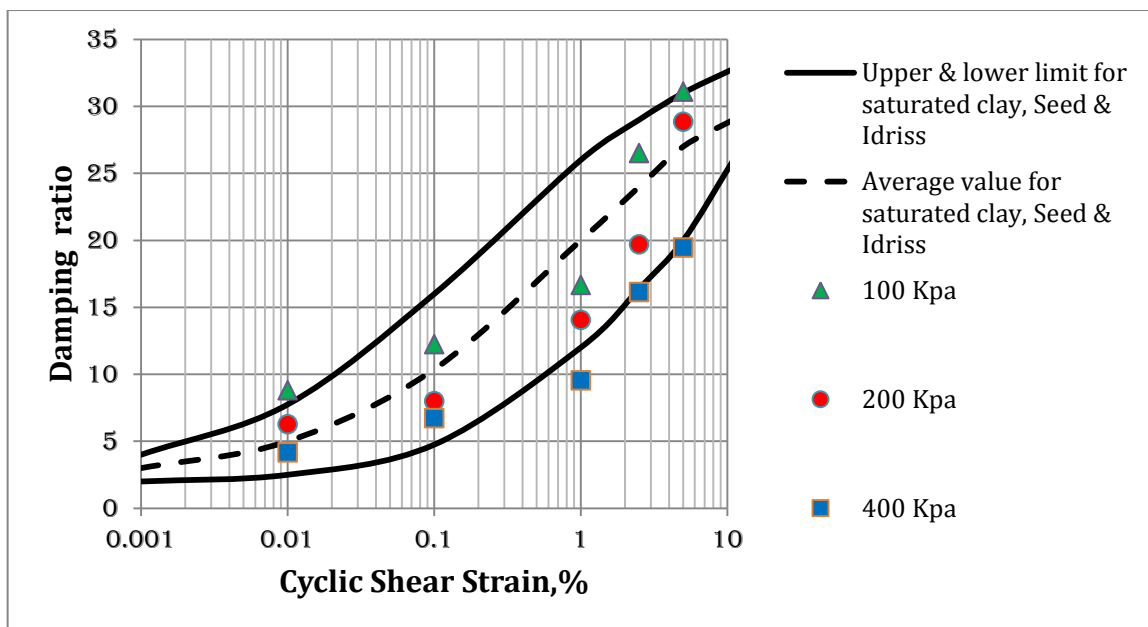


Figure 5.20: Comparison of damping ratio values of clay soil (PI=25) compared with curves developed for Saturated clay by Seed and Idriss (1970)

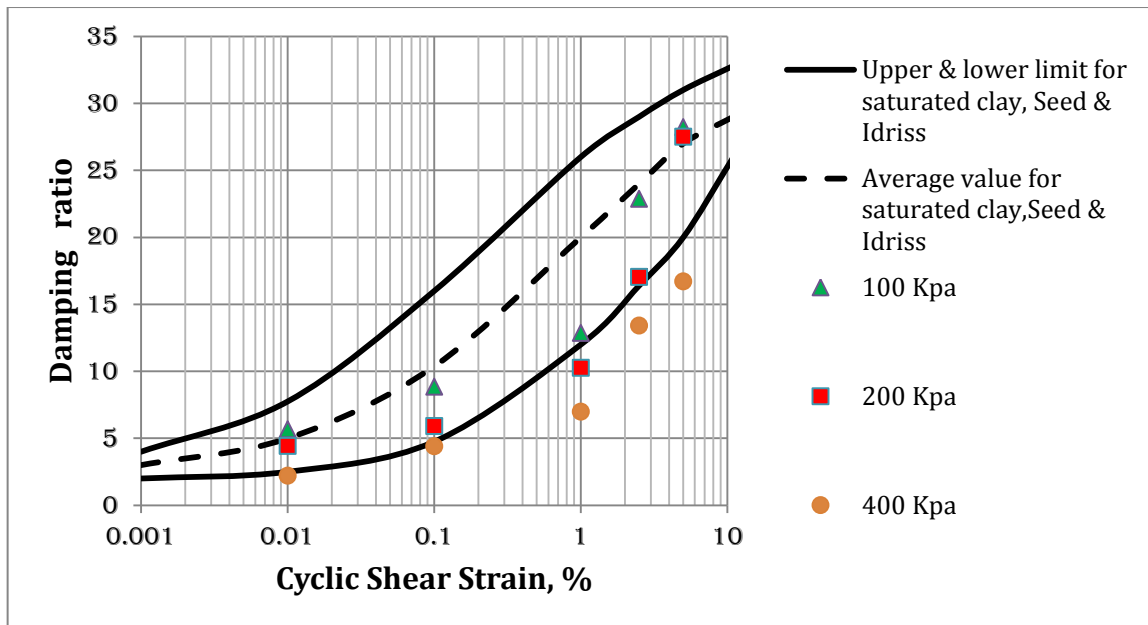


Fig 5.21: Comparison of damping ratio values of silt soil (PI=40) with curves developed for Saturated clay by Seed and Idriss (1970).

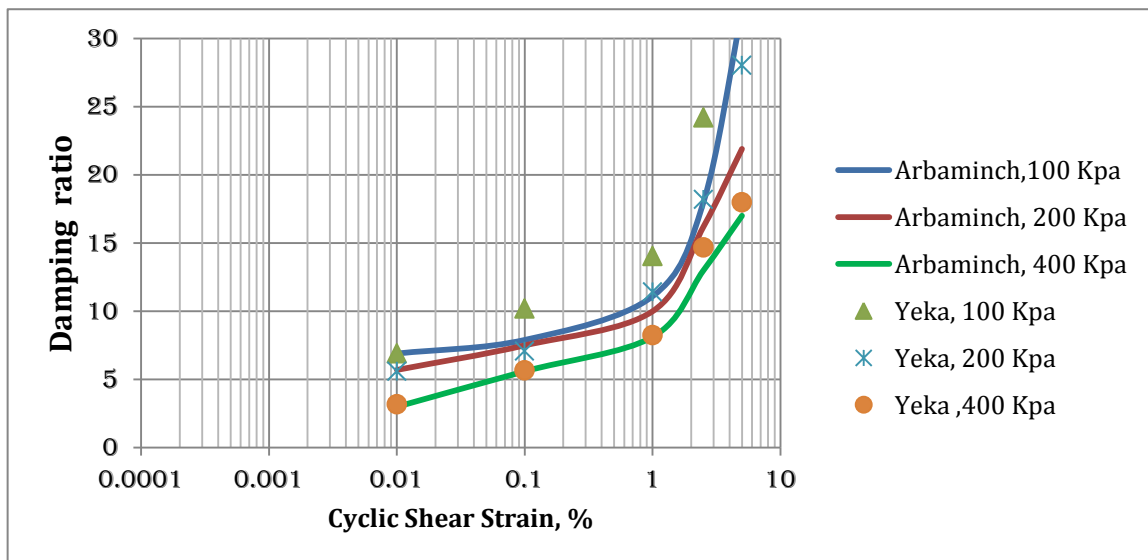


Figure 5.22: Comparison of damping ratio values of clay soil with curves developed for clay soils by Dimer (2013).

#### **5.4 Sources of errors in cyclic shear test**

It should be noted that each laboratory soil testing devices has their advantages and limitations. Shen et al. (1978) reported that the Norwegian geotechnical institute (NGI) type direct simple shear device may introduce an error of 5 to 15 % in shear modulus and damping ratio determination.

Deviations from known trends are usually credited to errors occurring during sample preparation and experimental testing of soils using cyclic simple shear apparatus. The sources of errors in the determination of G and D values of soils using cyclic shear apparatus are listed below.

- 1) Sample disturbance during retrieval of the samples from test pits, extruding of samples from Shelby tubes, may result in over estimation of damping ratio and under estimation of shear modulus of soils.
- 2) Limitation of the apparatus to accurately replicate actual field condition (stress, chemical, thermal and structural) at lower strain levels.
- 3) Maximum shear modulus is accurately determined from on-site field tests. In the absence of direct shear wave velocity measurement, estimation of maximum shear modulus using empirical relation causes a reduction of normalized shear modulus values.
- 4) The effect of partial boundary slippage at or immediately inside the interface between the soil specimen and the top and bottom caps of the simple shear apparatus results in an increase in the non-uniformity of stress distribution in the sample (Shen et al. 1978). It is therefore, important to provide the best possible seating between the sample and the caps.
- 5) Tatsuoka et al. (1995) reported that the effect of bedding error at the top and bottom ends of the specimen on the measured displacement may result in reduction in shear modulus and over estimation of damping ratios.
- 6) Due to delay in data acquisition for stresses and/or strain(s), the damping value of a specimen may be overestimated or underestimated depending on whether the stress and strain are recorded in a delayed manner.

7) Sample size and diameter to height ratio (D/H) affect the shear modulus and hysteretic damping ratio relationship with respect to shear strain. If test samples that are relatively thick and of small diameter are subjected to simple shear test conditions without the ability to develop complementary shear stresses on vertical boundaries, stress concentrations and non-uniformities in density distribution in the sample will lead to significant errors in test data. Carroll (1979) investigated the effect of sample size on G and D values of clay soil samples having diameter to height ratio (D/H) ranged from 3 to 9.4. He found that the smaller diameter samples were more resistant to shear by about 10 to 15 percent than the larger samples. This effect on shear modulus value is limited to low shear strains, less than 1 percent. In the shear strain range tested (from 0.01 to 1 percent), the percent of hysteresis damping were found to be higher.

8) During cyclic test the membrane surrounding the sample must provide adequate lateral strength to maintain a constant cross sectional area during consolidation and shear. The membrane will deform as the lateral stress increases, but this gives only a small error.

9) Experience of the operator also has an influence on shear modulus and damping ratio values.

The normalized shear modulus values in this paper for strains less than 0.01 % are lower than previously published data. It is also observed that, the damping ratio values are higher than previous literature trends. The possible sources of deviations from known trends are listed below.

- Sample disturbance during recovery of samples from manually dug test pits.
- Limitation of the cyclic shear apparatus to accurately estimate shear modulus value at lower strains (<0.01 %).
- Limited experience of the operator in conducting cyclic simple shear test.
- Use of empirical relations to estimate the maximum shear modulus resulted in deviation of normalized shear modulus values from previous literature trends.
- Boundary slippage at or immediately inside the interface between the soil specimen and the top and bottom caps of the simple shear apparatus results in an increase in the non-uniformity of stress distribution which may leads to over estimation of damping ratio value of soils.

## CHAPTER SIX

### 6 Conclusion and Recommendation

#### 6.1 Conclusion

The dynamic properties of soils found in Yeka subcity have been studied. To determine the pertinent dynamic properties ( $G$  and  $D$ ), cyclic simple shear test was performed on undisturbed samples from 6 test pits. Strain controlled cyclic simple shear tests were conducted for strain values of 0.01 %, 0.1 %, 1 %, 2.5 %, 5 % under axial stress of 100, 200 and 400 kPa. Furthermore, field density and index property of the soils were determined. Based on index properties and plasticity chart results the soils are classified into silt and clay soils. From the result of this investigation the following conclusions may be drawn:

- 1) The normalized shear modulus values of the studied soils agree with curves developed for clay soils of Arbaminch and very close to silty soils of Adama. However the values show slight scatter with silty soils of Ziway. The results of shear modulus and damping ratio curves of the investigated clay and silty soils are mostly within the curves developed by Seed and Idriss (1970).
- 2) The normalized shear modulus curves for the silt and clay soils at lower strains ( $<0.01$  %) are lower than the curves developed by Seed and Idriss (1970). This reduction could be due to sample preparation and testing conditions. However, the values at larger strain are within curves of Seed and Idriss (1970) and Vucetic and Dobry (1991).
- 3) The shear modulus values of the studied soils increase moderately for the first 10 cycles. But this effect slowly fades out with increasing number of cycles.
- 4) As seen from Figure 5.16 to 5.21, the damping ratio values of soils in this study for confining stress of 100 kPa and 200 kPa are within the curves developed by Seed and Idriss (1970) for clay soils. However, for confining stress of 400 kPa the values are outside the limits.

5) The normalized shear modulus values in this paper for strains less than 0.01 % are lower than previously published data. In contrast to this, the damping ratios are higher than trends in the literature. A number of sources of error could have contributed to this disagreement. The major ones include sample disturbance during recovery of samples from test pits, limitation of the cyclic shear apparatus to accurately estimate shear modulus value at lower strains (< 0.01 %), limited experience of the operator in conducting cyclic simple shear test, use of empirical relations to estimate the initial shear modulus and boundary slippage at or immediately inside the interface between the soil specimen and top and bottom caps resulting non uniform stress distribution in the sample. A more detailed discussion on the possible sources of errors is presents in section 5.4.

## 6.2 Recommendation

In this thesis, the dynamic properties of soils found in Yeka subcity of Addis Ababa are investigated. The following recommendations are made for future works.

- To increase the precision of test results, it is preferable to study the dynamic properties of the soils using cyclic triaxial apparatus.
- The research can be repeated by integrating on-site geophysical tests with laboratory tests.
- Future works should be conducted in the study of possible errors in dynamic testing of local soils using cyclic simple shear test apparatus.
- In this study samples were collected from 8 test pits. Hence, further studies should be carried out by increasing sample sizes.

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**APPENDICES**

**Appendix A: Test results for index properties of soils**

Table A-1: Liquid limit and Plastic limit results for TP 1

Trial no.	Liquid Limit			Plastic limit	
	1	2	3	1	2
No of blows	34	26	17		
Wt. Of moist soil + can(g)	43.14	44.87	43.78	27.25	27.87
Wt. of dry soil+ can(g)	33.18	34.04	33.18	25.65	26.19
Wt. of water(g)	9.95	10.83	10.60	1.60	1.68
Wt. of can(g)	20.49	20.45	20.12	21.07	21.34
Wt. Of dry soil(g)	12.69	13.59	13.06	4.58	4.85
Water content(g)	78.41	79.69	81.16	34.93	34.64
				Average PL(%)= 34.79	

Table A-2: Liquid limit and Plastic limit results for TP 2

Trial No	Liquid limit				Plastic limit		
	1	2	3	4	1	2	3
Can no	A/12	R/67	G/41	T/89			
Mass of can(g)	20.96	20.90	21.01	20.26	20.82	21.63	20.43
Mass of can +moist soil(g)	41.22	43.50	41.47	42.25	27.62	27.44	27.08
Mass of can +dry soil(g)	34.34	35.76	34.37	34.53	26.14	26.16	25.63
Mass of pore water (g)	6.88	7.74	7.10	7.72	1.48	1.28	1.45
Mass of dry soil(g)	13.38	14.86	13.36	14.27	5.32	4.53	5.20
Water content (%)	51.42	52.09	53.14	54.10	27.82	28.26	27.88
No of blows	32	27	23	16	Average PL(%)= 27.88		

Table A-3: Liquid limit and Plastic limit results for TP 3

Trial no.	Liquid Limit			Plastic limit	
	1	2	3	1	2
No of blows	33	26	18		
Wt. Of moist soil +can(g)	39.51	40.13	44.65	27.56	27.38
Wt. of dry soil+ can(g)	31.48	31.81	34.04	25.66	25.67
Wt. of water(g)	8.03	8.32	10.61	1.90	1.71
Wt. of can(g)	20.79	20.88	20.28	20.26	20.74
Wt. Of dry soil(g)	10.69	10.93	13.76	5.40	4.93
Water content(g)	75.12	76.12	77.11	35.19	34.69
				Average PL(%)= 34.94	

Table A-4: Liquid limit and Plastic limit results for TP 4

Trial No	Liquid limit				Plastic limit		
	1	2	3	4	1	2	3
Can no	Z/56	P/78	F19	K62			
Mass of can(g)	20.26	20.56	20.90	20.65	20.88	20.69	20.37
Mass of can +moist soil(g)	40.30	43.56	41.80	40.27	27.43	26.74	27.36
Mass of can +dry soil(g)	33.17	35.30	34.21	33.08	25.82	25.24	25.62
Mass of pore water (g)	7.13	8.26	7.59	7.19	1.61	1.50	1.74
Mass of dry soil(g)	12.91	14.74	13.31	12.43	4.94	4.55	5.25
Water content (%)	55.23	56.04	57.02	57.84	32.59	32.97	33.14
No of blows	33	26	19	16	Average PL(%)= 32.90		

Table A-5: Liquid limit and Plastic limit results for TP 5

Trial No	Liquid limit				Plastic limit		
	1	2	3	4	1	2	3
Can no	p/23	A/12	C/44	B/89			
Mass of can(g)	20.72	20.69	20.26	20.90	20.90	20.87	20.97
Mass of can +moist soil(g)	46.45	42.34	40.77	41.96	26.47	26.73	26.25
Mass of can +dry soil(g)	36.69	34.05	32.85	33.51	25.13	25.30	24.97
Mass of pore water (g)	9.76	8.29	7.92	8.45	1.34	1.43	1.28
Mass of dry soil(g)	15.97	13.36	12.59	13.31	4.23	4.43	4.00
Water content (%)	61.11	62.05	62.91	63.49	31.68	32.28	32.00
No of blows	35	27	20	17	Average PL(%)= 31.99		

Table A-6: Liquid limit and Plastic limit results for TP 6

Trial No	Liquid limit				Plastic limit		
	1	2	3	4	1	2	3
Can no	D/3	Q/6	T/4	A/2			
Mass of can(g)	20.29	20.91	20.86	20.25	20.73	20.57	20.42
Mass of can +moist soil(g)	40.59	39.40	42.69	44.79	26.57	25.96	26.28
Mass of can +dry soil(g)	31.44	31.02	32.76	33.59	24.88	24.39	24.57
Mass of pore water (g)	9.15	8.38	9.93	11.20	1.69	1.57	1.71
Mass of dry soil(g)	11.15	10.11	11.90	13.34	4.15	3.82	4.15
Water content (%)	82.06	82.89	83.45	83.96	40.72	41.10	41.20
No of blows	33	26	24	18	Average PL(%)= 41.01		

Table A-7: Liquid limit and Plastic limit results for TP 7

Trial No	Liquid limit				Plastic limit		
	1	2	3	4	1	2	3
Can no	C11	K22	G18	T45			
Mass of can(g)	13.86	14.15	14.06	15.62	14.34	13.27	13.80
Mass of can +moist soil(g)	28.70	31.42	29.40	30.42	15.70	14.61	15.16
Mass of can +dry soil(g)	22.68	24.32	23.02	24.22	15.32	14.24	14.78
Mass of pore water (g)	6.02	7.10	6.38	6.20	0.38	0.37	0.38
Mass of dry soil(g)	8.82	10.17	8.96	8.60	0.98	0.97	0.96
Water content (%)	68.25	69.81	71.21	72.09	38.78	38.14	38.46
No of blows	30	27	23	18	Average PL(%)= 38.4		

Table A-8: Liquid limit and Plastic limit results for TP 8

Trial No	Liquid limit			Plastic limit	
	1	2	3	1	2
Can no	A/66	T/14	B/2		
Mass of can(g)	20.10	20.12	20.00	20.69	20.98
Mass of can +moist soil(g)	44.27	45.02	45.67	27.47	26.94
Mass of can +dry soil(g)	33.30	33.59	33.80	25.36	25.08
Mass of pore water (g)	10.97	11.43	11.87	2.11	1.86
Mass of dry soil(g)	13.20	13.47	13.80	4.67	4.10
Water content (%)	83.11	84.86	86.01	45.18	45.37
No of blows	33	26	19	Average PL(%)= 45.27	

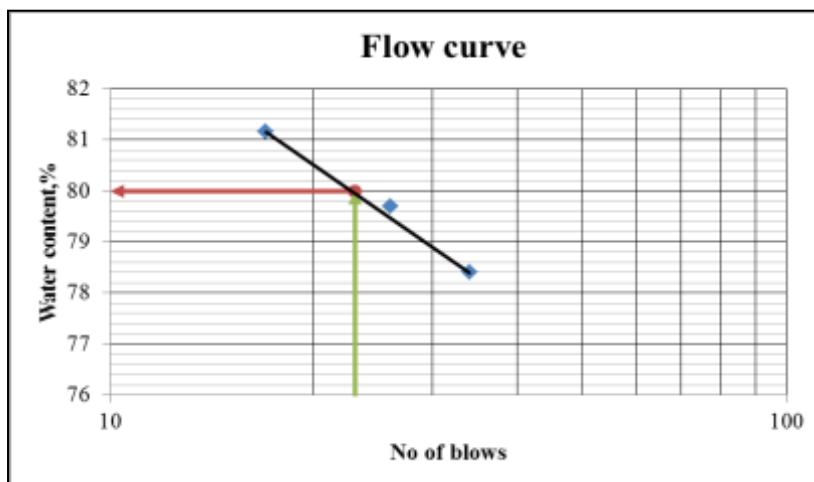
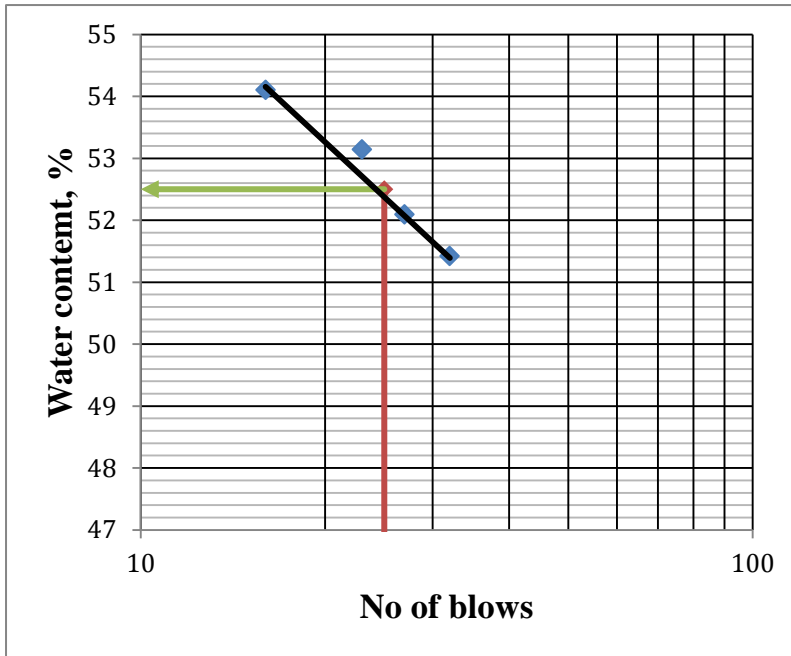


Figure A-1: Flow Curve for TP 1

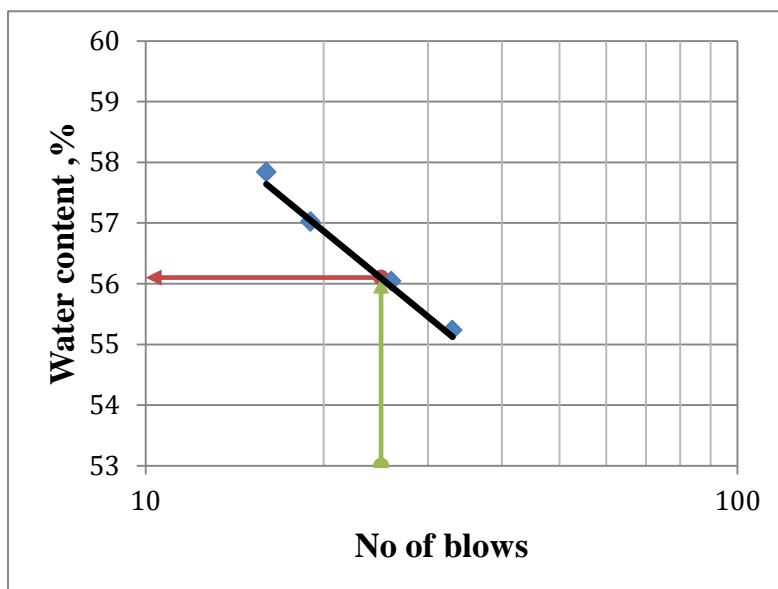


Liquid limit= 53

Plastic limit= 28

Plastic index= 25

Figure A-2: Flow Curve for TP 2

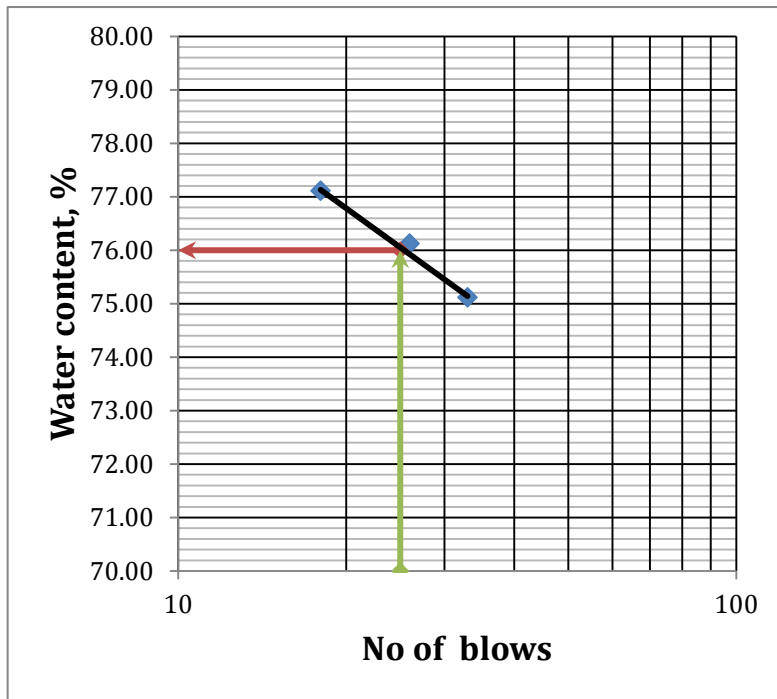


Liquid limit (%) = 56

Plastic limit (%) = 33

Plasticity Index (%) = 23

Figure A-3: Flow Curve for TP 3

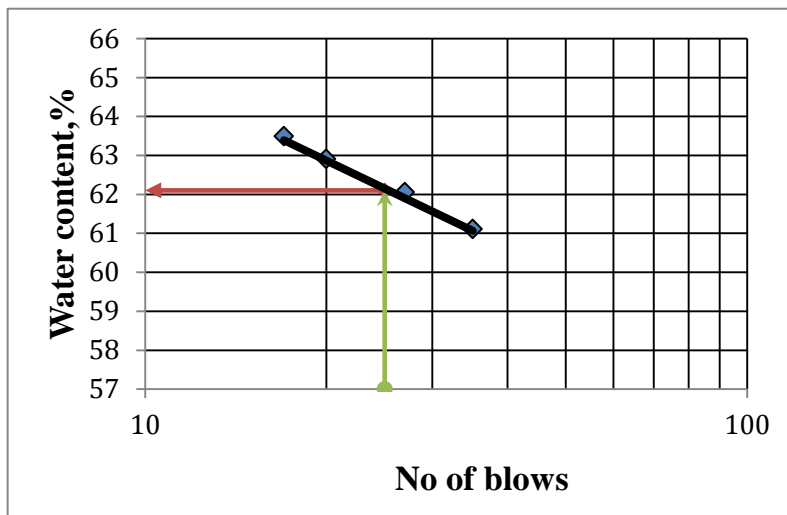


Liquid limit (%) = 76

Plastic limit (%) = 35

Plasticity Index (%) = 41

Figure A-4: Flow Curve for TP 4

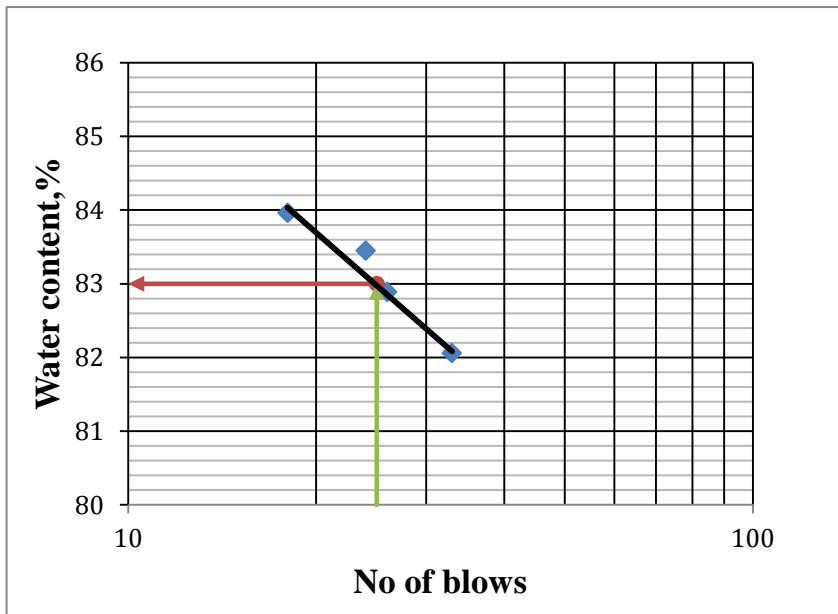


Liquid limit (%) = 62

Plastic limit (%) = 32

Plasticity Index (%) = 30

Figure A-5: Flow Curve for TP 5

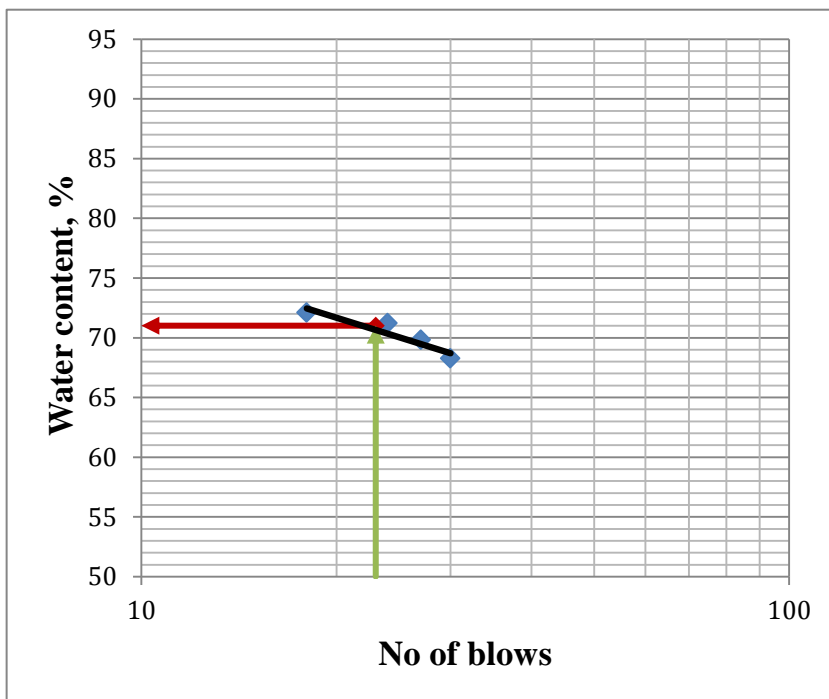


Liquid limit= 83

Plastic limit= 41

Plastic index= 42

Figure A-6: Flow Curve for TP 6



Liquid limit = 71

Plastic limit = 38

Plasticity index =33

Figure A-7: Flow Curve for TP 7

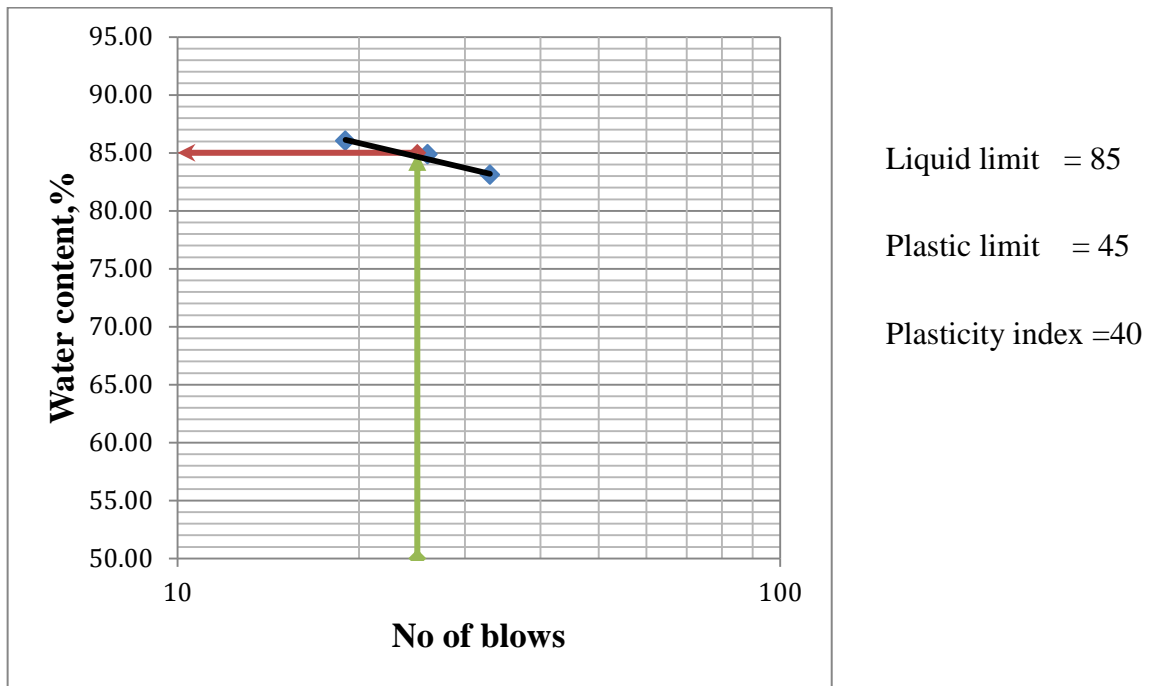


Figure A-8: Flow Curve for TP 8

**Appendix B: Field density and moisture content results**

Table B-1: Field density and moisture content for TP 1

Sample from test pit 1		
Weight of ring(g)	37.6	Diameter of ring(cm) 5
Weight of ring +soil(g)	111.3	Height of ring(cm) 2
Weight of Soil(g)	73.7	
Moisture content for soils		
Can.no	AB	868/A
Weight of empty can(g)	15.5	15.9
Weight of empty can +moist soil(g)	59.7	62.9
Weight of empty can+ dry soil(g)	45.6	48.5
Weight of pore water(g)	14.1	14.4
Weight of dry soil(g)	30.1	32.6
Water content (%)	46.84	44.17
Average water content (%)	45.51	
Bulk density(g/cm <sup>3</sup> )	1.88	
Dry density(g/cm <sup>3</sup> )	1.29	

Table B-2: Field density and moisture content for TP 2

Sample from test pit 2		
Weight of ring(g)	37.6	Diameter of ring(cm) 5
Weight of ring +soil(g)	109.1	Height of ring(cm) 2
Weight of Soil(g)	71.5	
Moisture content for soils		
Can.no	A/23	D/41
Weight of empty can(g)	16.1	15.8
Weight of empty can +moist soil(g)	50.7	49.6
Weight of empty can+ dry soil(g)	42.3	40.8
Weight of pore water(g)	8.4	9.1
Weight of dry soil(g)	26.2	24.7
Water content (%)	32.06	36.84
Average water content (%)	34.45	
Bulk density(g/cm <sup>3</sup> )	1.82	
Dry density(g/cm <sup>3</sup> )	1.35	

Table B-3: Field density and moisture content for TP 3

Sample from test pit 3		
Weight of ring(g)	68.1	Diameter of ring(cm) 5
Weight of ring +soil(g)	142.7	Height of ring(cm) 2
Weight of Soil(g)	74.6	
Moisture content for soils		
Can.no	A/17	G/66
Weight of empty can(g)	15.4	15.4
Weight of empty can +moist soil(g)	50.4	56
Weight of empty can+ dry soil(g)	40.3	44.4
Weight of pore water(g)	10.1	11.6
Weight of dry soil(g)	24.9	29.0
Water content (%)	39.44	40
Average water content (%)	40.28	
Bulk density(g/cm <sup>3</sup> )	1.90	
Dry density(g/cm <sup>3</sup> )	1.35	

Table B-4: Field density and moisture content for TP 4

Sample from test pit 4		
Weight of ring(g)	37.6	Diameter of ring(cm) 5
Weight of ring +soil(g)	108.7	Height of ring(cm) 2
Weight of Soil(g)	71.1	
Moisture content for soils		
Can.no	B/43	P/11
Weight of empty can(g)	16.1	15.8
Weight of empty can +moist soil(g)	51.8	50.66
Weight of empty can+ dry soil(g)	43.3	40.9
Weight of pore water(g)	8.5	9.76
Weight of dry soil(g)	27.2	25.1
Water content (%)	31.25	38.88
Average water content (%)	35.07	
Bulk density(g/cm <sup>3</sup> )	1.81	
Dry density(g/cm <sup>3</sup> )	1.34	

Table B-5: Field density and moisture content for TP 5

Sample from test pit 5		
Weight of ring(g)	72.14	Diameter of ring(cm) 5
Weight of ring +soil(g)	139.8	Height of ring(cm) 2
Weight of Soil(g)	67.66	
Moisture content for soils		
Can.no	A/32	Q/14
Weight of empty can(g)	15.4	15.6
Weight of empty can +moist soil(g)	82.69	81.2
Weight of empty can+ dry soil(g)	64.79	63.99
Weight of pore water(g)	17.9	17.21
Weight of dry soil(g)	49.39	48.39
Water content (%)	36.24	35.57
Average water content (%)	35.91	
Bulk density(g/cm <sup>3</sup> )	1.72	
Dry density(g/cm <sup>3</sup> )	1.27	

Table B-6: Field density and moisture content for TP 6

Sample from test pit 6		
Weight of ring(g)	37.6	Diameter of ring(cm) 5
Weight of ring +soil(g)	104.6	Height of ring(cm) 2
Weight of Soil(g)	67	
Moisture content for soils		
Can.no	B/33	T/74
Weight of empty can(g)	15.4	15.64
Weight of empty can +moist soil(g)	55.4	62.9
Weight of empty can+ dry soil(g)	44.9	48.6
Weight of pore water(g)	10.5	14.3
Weight of dry soil(g)	29.5	32.6
Water content (%)	35.59	43.39
Average water content (%)	39.49	
Bulk density(g/cm <sup>3</sup> )	1.706	
Dry density(g/cm <sup>3</sup> )	1.22	

Table B-7: Field density and moisture content for TP 7

Sample from test pit 7		
Weight of ring(g)	72.14	Diameter of ring(cm) 5
Weight of ring +soil(g)	142.50	Height of ring(cm) 2
Weight of Soil(g)	70.36	
Moisture content for soils		
Can.no	k/27	R/41
Weight of empty can(g)	15.4	15.6
Weight of empty can +moist soil(g)	85.76	84.71
Weight of empty can+ dry soil(g)	65.83	64.99
Weight of pore water(g)	19.93	19.72
Weight of dry soil(g)	50.43	49.39
Water content (%)	39.52	39.93
Average water content (%)	39.73	
Bulk density(g/cm <sup>3</sup> )	1.79	
Dry density(g/cm <sup>3</sup> )	1.28	

Table B-8: Field density and moisture content for TP 8

Sample from test pit 8		
Weight of ring(g)	37.6	Diameter of ring(cm) 5
Weight of ring +soil(g)	103.6	Height of ring(cm) 2
Weight of Soil(g)	66	
Moisture content for soils		
Can.no	M/15	Z/88
Weight of empty can(g)	16.3	16.5
Weight of empty can +moist soil(g)	56.3	63.8
Weight of empty can+ dry soil(g)	45.9	49.1
Weight of pore water(g)	10.4	14.7
Weight of dry soil(g)	29.6	32.6
Water content (%)	35.14	45.09
Average water content (%)	40.12	
Bulk density(g/cm <sup>3</sup> )	1.681	
Dry density(g/cm <sup>3</sup> )	1.2	

**Appendix C: Particle Size analysis results**

Combined particle size analysis result for all test pits

Test pit 1		Test pit 2		Test pit 3	
particel diameter,mm	percent of passing , %	particel diameter,mm	percent of passing , %	particel diameter,mm	percent of passing , %
63.5	100	63.5	100	63.5	100
50	100	50	100	50	100
37.5	100	37.5	100	37.5	100
25	100	25	100	25	100
19	100	19	100	19	100
12.5	100	12.5	100	12.5	100
9.5	100	9.5	99.87	9.5	100
6.3	100	6.3	99.4	6.3	100
4.75	99.8	4.75	98.5	4.75	99.79
2.36	99.5	2.36	97.1	2.36	99.53
2	99.3	2	96.39	2	99.40
1.18	99	1.18	95.46	1.18	99.20
0.85	98.8	0.85	94.2	0.85	99.13
0.6	98.5	0.6	92.86	0.6	98.99
0.425	98.2	0.425	91.90	0.425	98.21
0.3	97.9	0.3	89.36	0.3	97.36
0.15	97.1	0.15	88.62	0.15	95.80
0.075	96.4	0.075	86.87	0.075	93.74
0.028	88.4	0.03	79.8	0.0267	83.89
0.018	84.2	0.02	70.85	0.0172	79.63
0.01	80	0.012	64.53	0.0100	75.38
0.0075	75.8	0.0083	58.65	0.0071	69.85
0.005	69.5	0.006	54.29	0.0051	64.47
0.0028	61.1	0.002	46.37	0.0024	59.41
0.0012	54.8	0.0013	42.37	0.0011	55.71

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Test pit 4		Test pit 5		Test pit 6	
particel diameter,mm	percent of passing , %	particel diameter,mm	percent of passing , %	particel diameter,mm	percent of passing , %
63.50	100.0	63.50	100.0	63.5	100
50.00	100.0	50.00	100.0	50	100
37.50	100.0	37.50	100.0	37.5	100
25.00	100.0	25.00	100.0	25	100
19.00	100.0	19.00	100.0	19	100
12.50	100.0	12.50	100.0	12.5	100
9.50	99.0	9.50	100.0	9.5	100
6.30	98.8	6.30	100.0	6.3	100
4.75	98.4	4.75	99.9	4.75	99.79
2.36	97.7	2.36	99.5	2.36	99.53
2.00	97.2	2.00	99.1	2	99.40
1.18	96.7	1.18	98.4	1.18	99.20
0.85	96.1	0.85	97.0	0.85	99.13
0.60	95.3	0.60	96.4	0.6	98.99
0.425	94.7	0.425	94.7	0.425	98.91
0.30	93.2	0.30	93.2	0.3	98.86
0.15	92.3	0.15	91.4	0.15	98.80
0.075	90.6	0.075	89.0	0.075	98.74
0.030	83.6	0.030	84.1	0.0261	92.39
0.019	76.4	0.020	79.4	0.0169	89.20
0.011	68.3	0.012	74.4	0.0098	86.01
0.0082	62.7	0.0083	68.3	0.0070	82.61
0.006	60.1	0.006	63.2	0.0050	78.36
0.0028	53.2	0.0020	51.4	0.0024	70.17
0.0013	45.6	0.0013	47.4	0.0011	65.60

Test pit 7		Test pit 8	
particel diameter,mm	percent of passing , %	particel diameter,mm	percent of passing , %
63.5	100	63.5	100
50	100	50	100
37.5	100	37.5	100
25	100	25	100
19	100	19	100
12.5	100	12.5	100
9.5	100	9.5	100
6.3	100	6.3	100
4.75	99.8	4.75	99.9
2.36	99.5	2.36	99.5
2	99.3	2	99.4
1.18	99	1.18	99.2
0.85	98.8	0.85	99.1
0.6	98.5	0.6	99.0
0.425	98.2	0.425	98.9
0.3	97.9	0.3	98.9
0.15	96.24	0.15	98.80
0.075	95.4	0.075	96.23
0.028	90.36	0.0267	84.30
0.018	86.2	0.0172	80.63
0.01	82.15	0.0100	75.51
0.0075	79.8	0.0071	73.21
0.005	73.5	0.0051	62.79
0.0027	66.1	0.0022	55.21
0.0012	58.8	0.0011	51.3

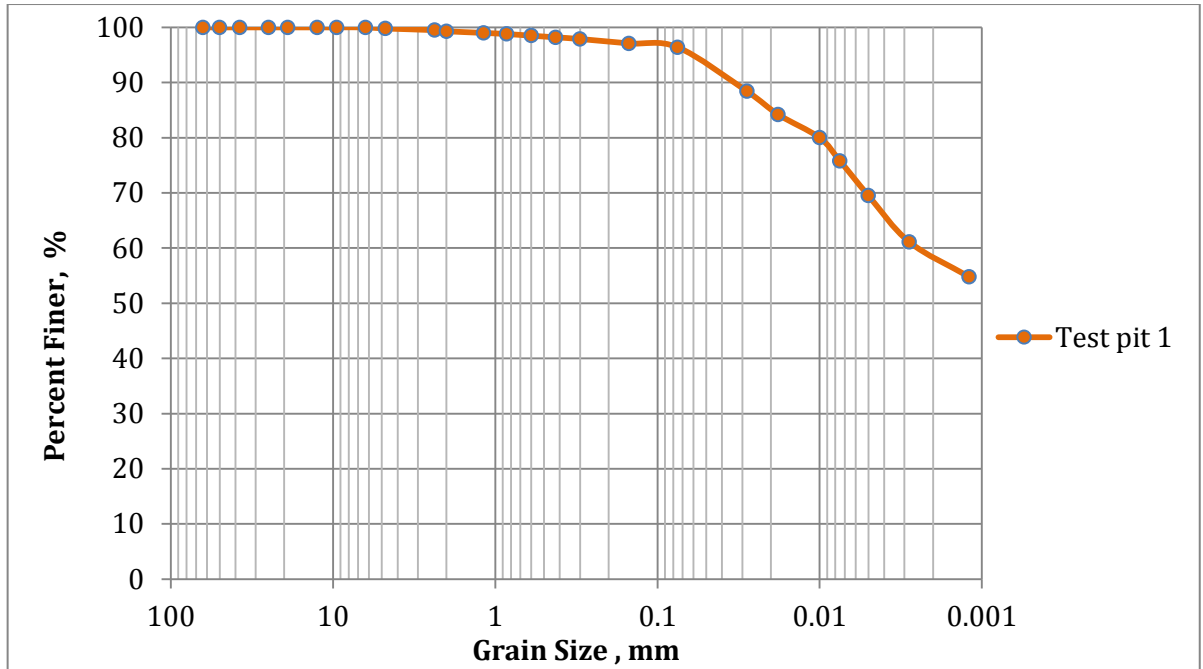


Figure C-1: Grain size distribution curve for TP 1

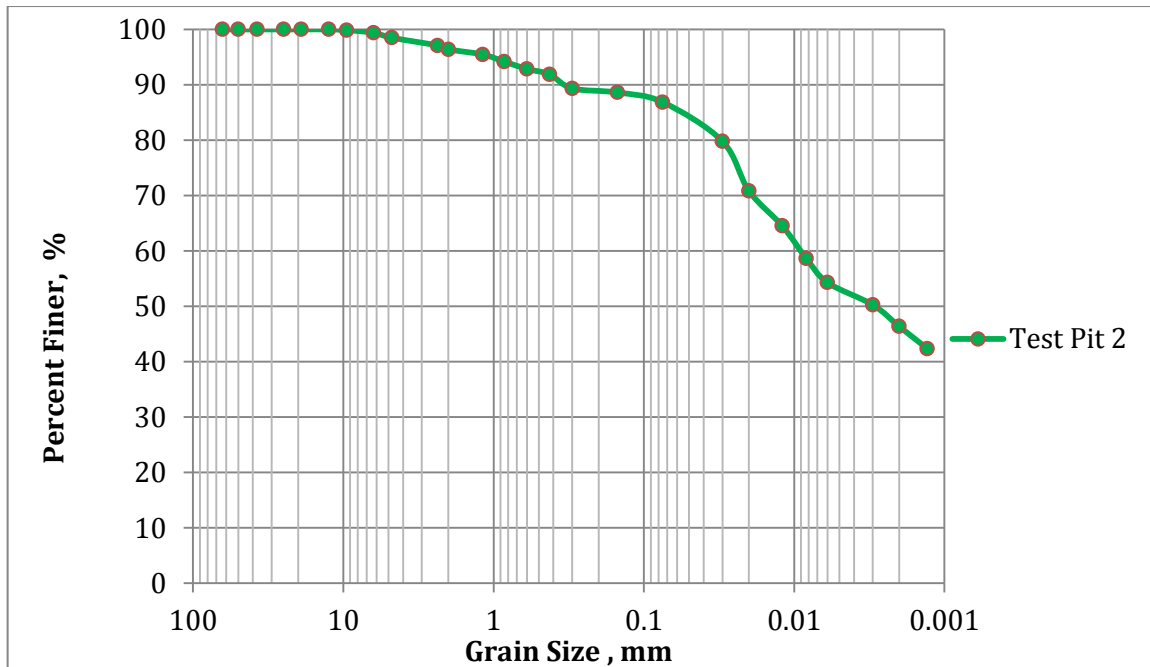


Figure C-2: Grain size distribution curve for TP 2



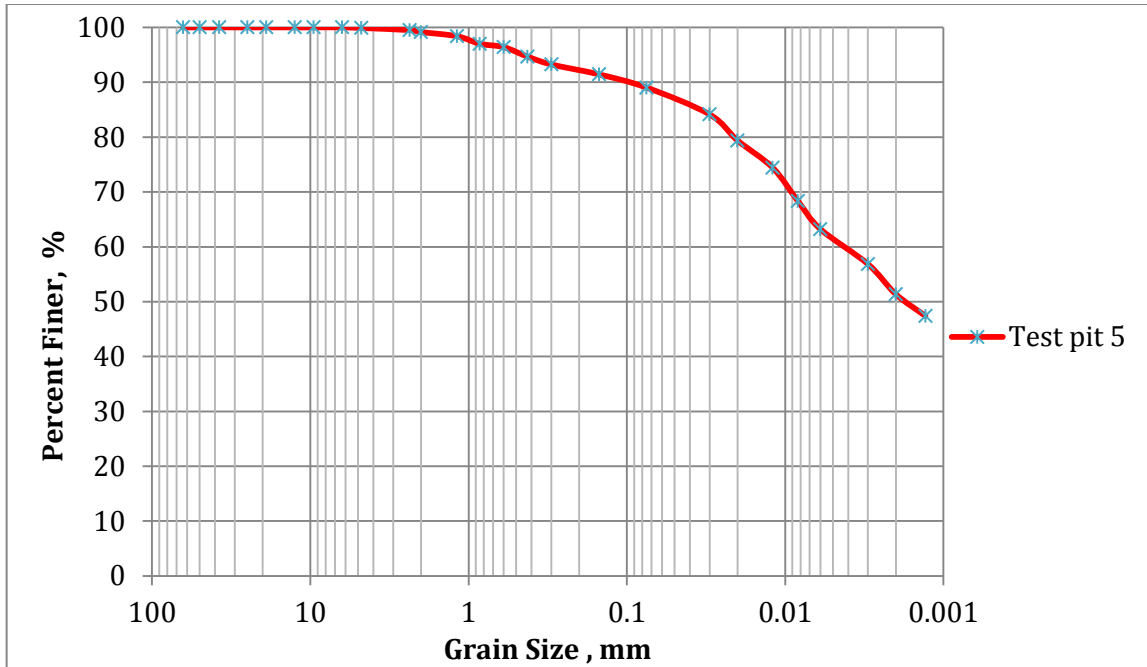


Figure C-5: Grain size distribution curve for TP 5

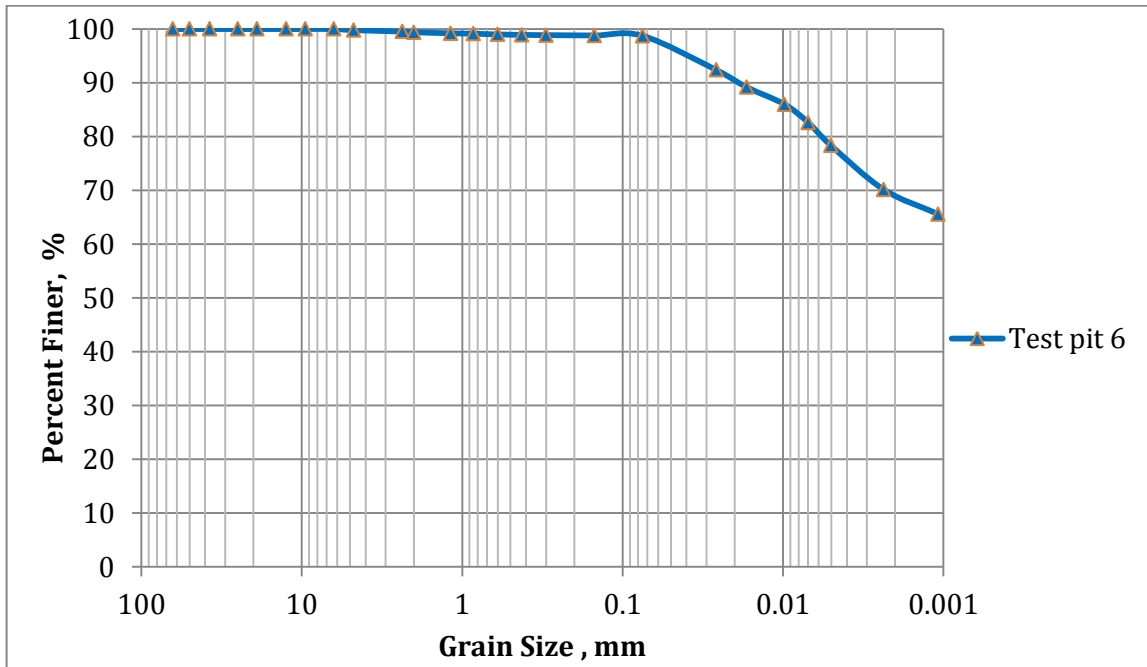


Figure C-6: Grain size distribution curve for TP 6

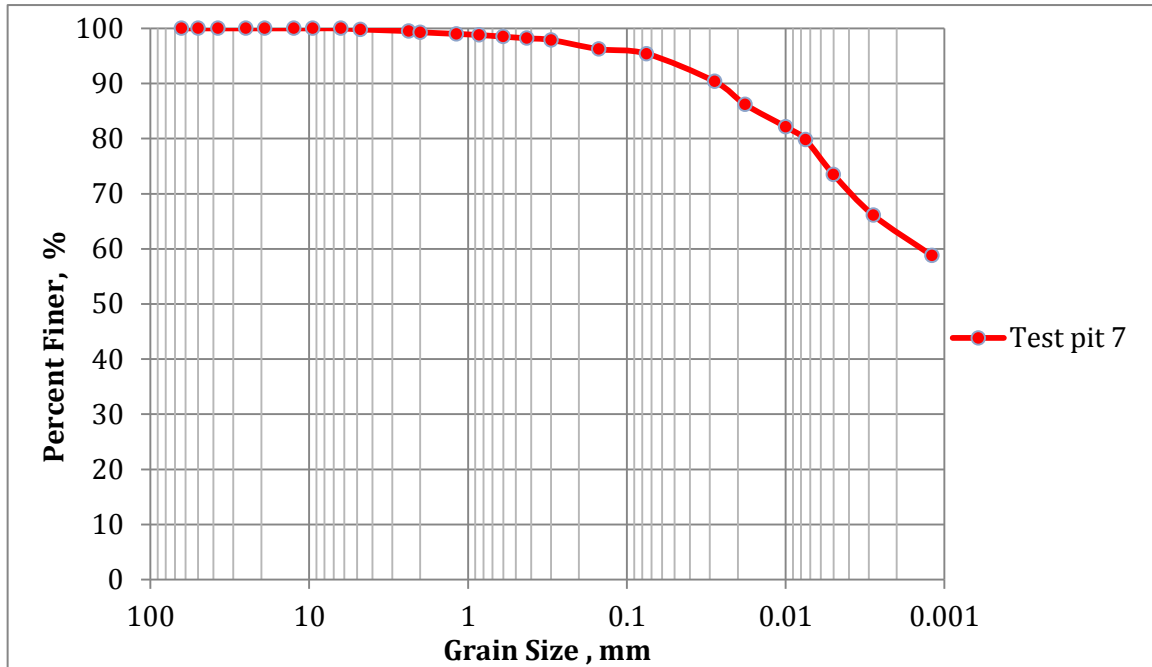


Figure C-7: Grain size distribution curve for TP 7

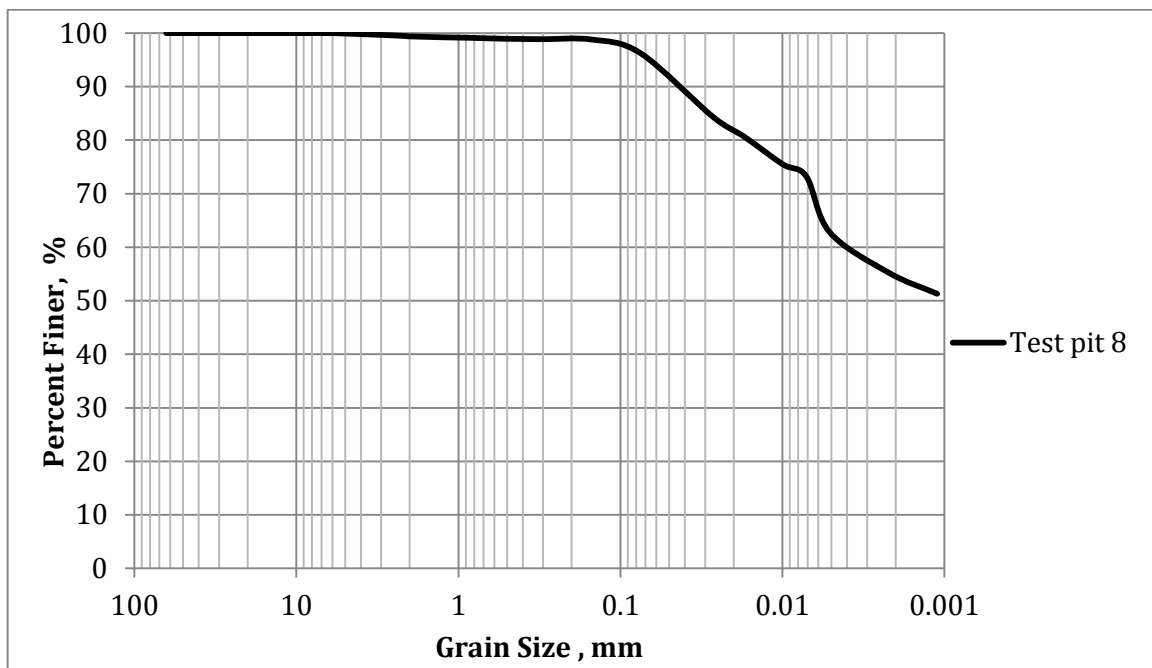


Figure C-8: Grain size distribution curve for TP 8

**Appendix D: Specific Gravity test results**

Table D -1: Specific Gravity result for TP 1

Determination No	1	2
Weight of Pycnometer	37.75	37.75
Weight of pycnometer + soil	47.75	47.75
Weight of pycnometer + water	92.57	92.56
Weight of pycnometer +soil + water	98.84	98.85
Specific gravity of soil at 20 °C	2.68	2.69
Average specific gravity	2.68	

Table D -2: Specific Gravity result for TP 2

Determination No	1	2
Weight of Pycnometer	37.75	37.75
Weight of pycnometer +soil + water	98.82	98.81
Weight of pycnometer + water	92.57	92.57
Specific gravity of soil at 20 °C	2.67	2.66
Average specific gravity	2.66	

Table D -3: Specific Gravity result for TP 3

Determination No	1	2
Weight of Pycnometer	37.75	37.75
Weight of Pycnometer + soil	47.75	47.75
Weight of pycnometer +soil + water	98.85	98.86
Weight of pycnometer + water	92.57	92.58
Specific gravity of soil at 20 °C	2.69	2.70
Average specific gravity	2.69	

Table D -4: Specific Gravity result for TP 4

Determination No	1	2
Wt. of pycnometer	37.75	37.75
Wt. of pycnometer + soil	47.75	47.75
Wt. of pycnometer +water	92.55	92.55
Wt. of pycnometer +soil+ water	98.79	98.80
Specific gravity 20 °C	2.66	2.67
Average specific gravity	2.66	

Table D -5: Specific Gravity result for TP 5

Determination No	1	2
Weight of Pycnometer	37.75	37.75
Weight of pycnometer +soil + water at	98.81	98.82
Weight of pycnometer + water	92.55	92.55
Specific gravity of soil at 20 <sup>0</sup> C	2.67	2.68
Average specific gravity	2.68	

Table D -6: Specific Gravity result for TP 6

Determination No	1	2
Weight of Pycnometer	37.75	37.76
Weight of pycnometer +soil + water	47.75	47.75
Weight of pycnometer + water	92.55	92.55
Specific gravity of soil at 20 <sup>0</sup> C	2.69	2.70
Average specific gravity	2.70	

Table D -7: Specific Gravity result for TP 7

Determination No	1	2
Weight of Pycnometer	70.01	70.01
Weight of pycnometer +soil + water	187.25	187.24
Weight of pycnometer + water	174.91	174.91
Specific gravity of soil at 20 <sup>0</sup> C	2.612	2.608
Average specific gravity	2.61	

Table D -8: Specific Gravity result for TP 8

Determination No	1	2
Weight of Pycnometer	22.78	22.78
Weight f pycnometer + soil	32.78	32.78
Weight of pycnometer + water	73.88	73.88
Weight of pycnometer +soil + water	80.18	80.19
Specific gravity of soil at 20 <sup>0</sup> C	2.70	2.71
Average specific gravity	2.71	

**Appendix E: Free Swell test results**

Table E-1: Free Swell test result for TP1

Determination	1	2
Weight of soil (g)	10	10
Initial volume	10	10
Final volume	16	15.7
Free swell (%)	60	57
Average Free swell (%)	59	

Table E-2: Free Swell test result for TP2

Determination	1	2
Weight of soil (g)	10	10
Initial volume	10	10
Final volume	15.7	16.5
Free swell (%)	57	65
Average Free swell (%)	61	

Table E-3: Free Swell test result for TP3

Determination	1	2
Weight of soil (g)	10	10
Initial volume	10	10
Final volume	21.1	21.9
Free swell (%)	111	119
Average Free swell (%)	115	

Table E-4: Free Swell test result for TP4

Determination	1	2
Weight of soil (g)	10	10
Initial volume	10	10
Final volume	15.9	16.1
Free swell (%)	59	61
Average Free swell (%)	60	

Table E-5: Free Swell test result for TP5

Determination	1	2
Weight of soil (g)	10	10
Initial volume	10	10
Final volume	17.9	18.1
Free swell (%)	79	81
Average Free swell (%)	80	

Table E-6: Free Swell test result for TP6

Determination	1	2
Weight of soil (g)	10	10
Initial volume	10	10
Final volume	23	22.6
Free swell (%)	130	126
Average Free swell (%)	128	

Table E-7: Free Swell test result for TP7

Determination	1	2
Weight of soil (g)	10	10
Initial volume	10	10
Final volume	19	19.25
Free swell (%)	90	92.5
Average Free swell (%)	91	

Table E-8: Free Swell test result for TP8

Determination	1	2
Weight of soil (g)	10	10
Initial volume	10	10
Final volume	18.1	17.8
Free swell (%)	81	78
Average Free swell (%)	80	

**Appendix F: Cyclic simple shear results**

Table F-1: Shear modulus and damping ratio values for Test Pit 2 under axial stress of 100 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	13.01	8.09	1.81	0.65	0.11	9.06	12.62	16.94	26.63	33.93
2	13.45	8.25	1.90	0.81	0.30	8.97	12.52	16.85	26.62	32.53
3	13.60	8.30	1.92	0.83	0.38	8.96	12.44	16.75	26.59	32.38
4	13.73	8.41	2.01	0.91	0.41	8.87	12.37	16.66	26.55	32.31
5	13.82	8.53	2.07	0.95	0.44	8.80	12.23	16.65	26.51	32.09
6	13.86	8.58	2.10	0.96	0.47	8.76	12.11	16.58	26.49	31.45
7	13.91	8.59	2.10	0.98	0.47	8.73	12.01	16.08	26.31	31.20
8	13.92	8.60	2.09	0.98	0.47	8.72	12.01	15.74	25.97	31.12
9	13.93	8.58	2.10	0.98	0.48	8.72	12.00	15.67	25.86	31.09
10	13.96	8.61	2.12	1.00	0.50	8.70	11.97	15.58	25.37	30.98
11	13.97	8.59	2.13	1.01	0.52	8.69	11.96	15.51	25.25	30.97
12	13.99	8.62	2.14	1.01	0.54	8.69	11.95	15.50	25.23	30.97
13	14.01	8.67	2.15	1.03	0.55	8.68	11.95	15.48	25.23	30.96
14	14.03	8.60	2.15	1.04	0.55	8.67	11.94	15.47	25.21	30.83
15	13.99	8.65	2.16	1.04	0.53	8.66	11.93	15.41	25.16	30.74
16	14.07	8.65	2.17	1.04	0.55	8.66	11.92	15.32	25.16	30.61
17	14.09	8.58	2.18	1.05	0.55	8.65	11.90	15.30	25.06	30.54
18	14.10	8.62	2.19	1.06	0.54	8.64	11.89	15.30	25.04	30.44
19	14.12	8.63	2.19	1.06	0.54	8.63	11.88	15.29	25.03	30.04
20	14.15	8.62	2.17	1.08	0.58	8.62	11.86	15.27	25.01	29.98
21	14.16	8.60	2.16	1.09	0.55	8.61	11.85	15.26	25.01	29.95
22	14.10	8.69	2.19	1.09	0.55	8.60	11.83	15.25	25.01	29.92
23	14.18	8.69	2.18	1.10	0.56	8.60	11.82	15.25	25.01	29.87
24	14.18	8.62	2.19	1.08	0.56	8.59	11.81	15.24	25.01	29.81
25	14.16	8.62	2.20	1.09	0.52	8.59	11.81	15.24	25.01	29.79
26	14.18	8.61	2.21	1.10	0.56	8.58	11.80	15.23	24.82	29.78
27	14.21	8.63	2.22	1.11	0.56	8.56	11.79	15.21	24.82	29.76
28	14.29	8.62	2.24	1.13	0.56	8.55	11.71	15.21	24.82	29.72
29	14.30	8.62	2.25	1.12	0.53	8.54	11.69	15.19	24.81	29.64
30	14.31	8.66	2.25	1.14	0.57	8.53	11.66	15.18	24.81	29.61
31	14.32	8.67	2.24	1.14	0.56	8.52	11.66	15.18	24.80	29.61
32	14.34	8.69	2.25	1.16	0.56	8.51	11.65	15.15	24.79	29.57
33	14.35	8.68	2.26	1.16	0.57	8.50	11.64	15.11	24.78	29.55
34	14.39	8.67	2.27	1.17	0.57	8.50	11.63	15.11	24.76	29.54
35	14.39	8.70	2.28	1.18	0.57	8.49	11.62	14.79	24.71	29.52
36	14.40	8.67	2.29	1.19	0.57	8.48	11.62	14.76	24.49	29.51
37	14.40	8.68	2.29	1.19	0.58	8.48	11.61	14.76	24.33	29.50
38	14.41	8.69	2.30	1.20	0.58	8.47	11.60	14.73	24.30	29.49
39	14.42	8.70	2.31	1.22	0.58	8.47	11.59	14.67	24.25	29.48
40	14.43	8.72	2.32	1.23	0.60	8.47	11.59	14.64	24.24	29.47

Table F-2: Shear modulus and damping ratio values for Test Pit 2 under axial stress of 200 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	15.54	9.11	3.54	1.31	0.62	6.53	9.17	14.80	20.64	28.99
2	15.61	9.10	3.54	1.35	0.64	6.42	9.11	14.77	20.59	28.95
3	15.72	9.38	3.55	1.38	0.75	6.34	9.06	14.67	20.54	28.89
4	15.79	9.44	3.56	1.48	0.86	6.32	8.99	14.61	20.45	28.87
5	16.30	10.02	4.34	1.52	0.90	6.27	7.99	14.05	19.70	28.85
6	16.35	10.07	4.37	1.55	0.92	6.25	7.77	14.04	19.68	28.83
7	16.35	10.09	4.39	1.60	0.99	6.21	7.77	14.03	19.67	28.81
8	16.38	10.16	4.43	1.62	1.03	6.21	7.76	14.01	19.65	28.69
9	16.46	10.16	4.45	1.63	1.05	6.20	7.75	13.99	19.64	28.68
10	16.56	10.17	4.51	1.65	1.06	6.19	7.74	13.98	19.63	28.58
11	16.57	10.18	4.52	1.65	1.08	6.18	7.72	13.95	19.60	28.55
12	16.61	10.18	4.53	1.68	1.09	6.13	7.71	13.95	19.58	28.51
13	16.65	10.19	4.53	1.68	1.09	5.94	7.69	13.93	19.57	28.51
14	16.66	10.19	4.54	1.69	1.10	5.66	7.69	13.90	19.55	28.40
15	16.71	10.19	4.54	1.70	1.11	5.47	7.65	13.88	19.54	28.31
16	16.72	10.19	4.55	1.71	1.13	5.43	7.63	13.87	19.52	28.22
17	16.73	10.20	4.56	1.72	1.14	5.42	7.60	13.86	19.51	28.19
18	16.75	10.20	4.57	1.74	1.15	5.41	7.57	13.86	19.50	28.16
19	16.79	10.20	4.57	1.75	1.17	5.39	7.54	13.85	19.50	28.11
20	16.79	10.21	4.58	1.76	1.20	5.38	7.53	13.84	19.49	28.11
21	16.82	10.21	4.59	1.76	1.20	5.37	7.46	13.82	19.45	28.04
22	16.82	10.21	4.60	1.77	1.20	5.36	7.45	13.82	19.44	28.04
23	16.83	10.22	4.61	1.78	1.21	5.34	7.39	13.80	19.41	28.03
24	16.85	10.23	4.62	1.79	1.22	5.34	7.36	13.78	19.37	28.01
25	16.85	10.23	4.63	1.80	1.23	5.33	7.32	13.77	19.35	27.95
26	16.86	10.24	4.64	1.81	1.24	5.32	7.31	13.76	19.33	27.93
27	16.88	10.24	4.65	1.81	1.25	5.29	7.30	13.74	19.32	27.92
28	16.89	10.26	4.66	1.81	1.25	5.28	7.29	13.73	19.32	27.91
29	16.89	10.27	4.66	1.83	1.27	5.27	7.28	13.72	19.31	27.91
30	16.91	10.28	4.66	1.84	1.27	5.25	7.28	13.72	19.30	27.89
31	16.93	10.30	4.66	1.85	1.28	5.24	7.27	13.72	19.30	27.88
32	16.95	10.31	4.66	1.86	1.28	5.22	7.26	13.71	19.28	27.88
33	16.96	10.31	4.67	1.88	1.29	5.21	7.24	13.70	19.28	27.87
34	16.98	10.32	4.67	1.88	1.30	5.19	7.23	13.69	19.27	27.86
35	16.99	10.33	4.68	1.88	1.31	5.18	7.21	13.68	19.26	27.85
36	16.99	10.34	4.68	1.89	1.31	5.17	7.20	13.67	19.25	27.84
37	17.00	10.35	4.69	1.90	1.32	5.16	7.19	13.67	19.24	27.84
38	17.00	10.36	4.69	1.91	1.33	5.15	7.18	13.65	19.24	27.82
39	17.04	10.38	4.70	1.92	1.34	5.14	7.17	13.64	19.23	27.81
40	17.04	10.39	4.71	1.93	1.34	5.13	7.16	13.63	19.22	27.80

Table F-3: Shear modulus and damping ratio values for Test Pit 2 under axial stress of 400 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	19.68	13.15	8.00	4.61	1.32	4.41	7.22	9.75	16.55	20.16
2	19.99	13.43	8.33	5.16	1.95	4.26	7.02	9.66	16.33	19.87
3	20.14	13.79	8.42	5.34	2.13	4.24	6.73	9.65	16.21	19.80
4	20.26	14.02	8.53	5.36	2.27	4.16	6.71	9.57	16.15	19.58
5	20.38	14.17	8.58	5.39	2.35	4.16	6.71	9.54	16.12	19.45
6	20.40	14.23	8.51	5.38	2.38	3.94	6.68	9.49	16.11	18.99
7	20.42	14.28	8.59	5.39	2.41	3.94	6.67	9.36	16.10	18.89
8	20.43	14.28	8.60	5.39	2.51	3.90	6.66	9.20	16.09	18.75
9	20.49	14.29	8.63	5.45	2.52	3.90	6.66	9.03	16.07	18.75
10	20.53	14.36	8.71	5.46	2.52	3.87	6.65	9.00	16.09	18.72
11	20.58	14.38	8.71	5.50	2.52	3.87	6.64	8.84	16.08	18.72
12	20.60	14.43	8.70	5.51	2.52	3.85	6.64	8.78	16.08	18.69
13	20.66	14.43	8.71	5.51	2.53	3.85	6.61	8.70	16.08	18.65
14	20.66	14.43	8.71	5.54	2.58	3.82	6.60	8.65	16.07	18.49
15	20.72	14.45	8.71	5.54	2.56	3.82	6.58	8.59	16.07	18.37
16	20.72	14.47	8.72	5.59	2.57	3.82	6.58	8.49	16.07	18.37
17	20.72	14.48	8.74	5.63	2.57	3.79	6.57	8.40	16.06	18.36
18	20.74	14.51	8.75	5.64	2.58	3.78	6.51	8.39	16.05	18.35
19	20.77	14.61	8.87	5.64	2.61	3.75	6.46	8.32	16.05	18.35
20	20.78	14.52	8.78	5.69	2.61	3.72	6.36	8.31	16.00	18.31
21	20.79	14.65	8.89	5.67	2.62	3.71	6.35	8.30	15.85	18.25
22	20.79	14.67	8.90	5.68	2.62	3.71	6.28	8.29	15.83	18.06
23	20.81	14.69	8.91	5.71	2.63	3.69	6.25	8.28	15.78	18.06
24	20.84	14.75	8.97	5.71	2.64	3.67	6.22	8.27	15.75	18.01
25	20.86	14.73	8.92	5.70	2.63	3.67	6.21	8.26	15.74	17.84
26	20.86	14.75	8.99	5.69	2.64	3.66	6.20	8.26	15.73	17.80
27	20.86	14.78	9.10	5.71	2.66	3.65	6.20	8.22	15.71	17.79
28	20.87	14.76	9.06	5.72	2.64	3.63	6.17	8.20	15.68	17.79
29	20.88	14.83	9.17	5.70	2.65	3.62	6.16	8.18	15.67	17.79
30	20.92	14.84	9.16	5.72	2.65	3.60	6.14	8.15	15.65	17.79
31	20.95	14.88	9.13	5.75	2.66	3.59	6.14	8.15	15.65	17.77
32	20.97	14.85	9.14	5.74	2.65	3.57	6.14	8.13	15.64	17.74
33	20.98	14.89	9.13	5.76	2.66	3.57	6.12	8.11	15.63	17.74
34	21.02	14.90	9.12	5.77	2.68	3.55	6.11	8.08	15.56	17.72
35	21.03	14.91	9.11	5.78	2.68	3.54	6.08	8.08	15.51	17.72
36	21.08	14.92	9.11	5.78	2.69	3.53	6.07	8.07	15.42	17.71
37	21.08	14.92	9.10	5.79	2.69	3.53	6.05	8.07	15.41	17.69
38	21.11	14.94	9.09	5.80	2.70	3.51	6.03	8.06	15.40	17.69
39	21.12	14.95	9.09	5.81	2.71	3.48	6.03	8.06	15.39	17.68
40	21.14	14.95	9.08	5.81	2.71	3.47	6.02	8.05	15.39	17.67

Table F-4: Shear modulus and damping ratio values for Test Pit 4 under axial stress of 100 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	13.24	8.49	1.77	0.76	0.25	9.38	12.94	17.27	26.95	34.95
2	13.48	8.66	1.86	0.83	0.32	9.29	12.84	17.17	26.94	32.85
3	13.63	8.72	1.88	0.85	0.41	9.28	12.76	17.07	26.87	32.70
4	13.76	8.83	1.97	0.93	0.45	9.19	12.69	16.99	26.81	32.63
5	13.85	8.95	2.03	0.98	0.48	9.12	12.55	16.90	26.92	32.41
6	13.89	9.00	2.05	0.99	0.51	9.08	12.43	16.97	26.83	31.77
7	13.95	9.02	2.06	1.00	0.51	9.05	12.33	16.40	26.63	31.52
8	13.96	9.05	2.06	1.00	0.51	9.04	12.33	16.06	26.29	31.44
9	13.98	9.06	2.06	1.01	0.52	9.03	12.32	15.99	26.18	31.41
10	13.99	9.08	2.08	1.03	0.57	9.02	12.29	15.91	25.69	31.29
11	13.99	9.10	2.09	1.03	0.57	9.02	12.29	15.83	25.57	31.29
12	14.00	9.12	2.10	1.04	0.57	9.01	12.27	15.82	25.55	31.30
13	14.02	9.13	2.11	1.05	0.57	9.00	12.27	15.80	25.53	31.28
14	14.03	9.14	2.11	1.06	0.57	8.99	12.26	15.79	25.55	31.15
15	14.05	9.16	2.12	1.06	0.58	8.98	12.25	15.59	25.48	31.06
16	14.10	9.16	2.12	1.07	0.59	8.98	12.24	15.64	25.48	30.93
17	14.13	9.17	2.13	1.07	0.60	8.97	12.22	15.55	25.38	30.86
18	14.13	9.19	2.13	1.07	0.62	8.97	12.22	15.73	25.36	30.76
19	14.14	9.20	2.14	1.08	0.64	8.96	12.20	15.62	25.35	30.36
20	14.15	9.21	2.14	1.08	0.67	8.95	12.19	15.62	25.33	30.31
21	14.17	9.21	2.15	1.08	0.67	8.94	12.17	15.57	25.33	30.27
22	14.20	9.23	2.15	1.09	0.68	8.92	12.16	15.56	25.33	30.24
23	14.20	9.24	2.15	1.08	0.70	8.92	12.14	15.51	25.33	30.19
24	14.22	9.26	2.15	1.11	0.70	8.91	12.13	15.54	25.33	30.14
25	14.22	9.26	2.16	1.13	0.70	8.91	12.13	15.62	25.33	30.11
26	14.23	9.28	2.18	1.14	0.71	8.90	12.12	15.58	25.14	30.11
27	14.25	9.29	2.18	1.14	0.73	8.88	12.11	15.57	25.13	30.08
28	14.33	9.30	2.20	1.16	0.73	8.87	12.03	15.56	25.12	30.04
29	14.34	9.31	2.20	1.17	0.74	8.86	12.01	15.51	25.12	29.97
30	14.35	9.32	2.20	1.18	0.75	8.85	11.99	15.54	25.14	29.94
31	14.35	9.34	2.20	1.19	0.76	8.85	11.98	15.51	25.12	29.94
32	14.38	9.35	2.22	1.20	0.77	8.83	11.97	15.47	25.14	29.89
33	14.39	9.36	2.22	1.22	0.77	8.82	11.96	15.43	25.13	29.86
34	14.41	9.36	2.22	1.22	0.78	8.82	11.95	15.43	25.12	29.87
35	14.41	9.37	2.23	1.23	0.76	8.81	11.94	14.99	25.04	29.84
36	14.42	9.38	2.23	1.24	0.79	8.80	11.93	14.96	24.81	29.82
37	14.42	9.38	2.23	1.26	0.80	8.80	11.93	15.05	24.65	29.82
38	14.43	9.39	2.23	1.27	0.81	8.80	11.93	15.08	24.62	29.81
39	14.44	9.40	2.26	1.28	0.81	8.79	11.92	15.11	24.57	29.80
40	14.45	9.41	2.28	1.28	0.83	8.79	11.92	15.19	24.56	29.79

Table F-5: Shear modulus and damping ratio values for Test Pit 4 under axial stress of 200 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	15.49	9.07	3.99	1.31	0.56	6.85	9.49	15.12	20.96	29.31
2	15.53	9.08	4.04	1.35	0.58	6.74	9.43	15.09	20.91	29.27
3	15.61	9.35	4.11	1.38	0.69	6.67	9.38	14.99	20.86	29.21
4	16.04	9.42	4.19	1.48	0.79	6.64	9.31	14.93	20.77	29.19
5	16.12	9.99	4.25	1.52	0.83	6.59	8.31	14.37	20.02	29.17
6	16.30	10.04	4.28	1.55	0.85	6.57	8.09	14.36	20.01	29.15
7	16.30	10.07	4.30	1.59	0.92	6.53	8.09	14.35	19.99	29.13
8	16.33	10.13	4.34	1.62	0.96	6.53	8.08	14.33	19.97	29.01
9	16.40	10.13	4.36	1.63	0.97	6.52	8.07	14.32	19.96	29.00
10	16.50	10.14	4.42	1.65	0.99	6.51	8.06	14.30	19.95	28.91
11	16.51	10.15	4.43	1.65	1.01	6.50	8.04	14.27	19.92	28.87
12	16.56	10.15	4.44	1.67	1.02	6.45	8.03	14.27	19.90	28.83
13	16.59	10.16	4.44	1.67	1.02	6.26	8.01	14.25	19.89	28.83
14	16.61	10.16	4.44	1.69	1.02	5.99	8.01	14.23	19.87	28.72
15	16.65	10.16	4.44	1.70	1.03	5.79	7.97	14.20	19.86	28.63
16	16.67	10.16	4.45	1.71	1.05	5.75	7.95	14.19	19.84	28.54
17	16.67	10.17	4.46	1.72	1.06	5.74	7.92	14.18	19.83	28.51
18	16.69	10.17	4.47	1.73	1.08	5.73	7.89	14.18	19.82	28.48
19	16.73	10.17	4.48	1.75	1.09	5.71	7.87	14.17	19.82	28.43
20	16.73	10.18	4.49	1.76	1.12	5.70	7.85	14.16	19.81	28.43
21	16.76	10.18	4.50	1.76	1.12	5.70	7.79	14.14	19.77	28.36
22	16.76	10.18	4.51	1.77	1.13	5.69	7.77	14.14	19.76	28.36
23	16.77	10.20	4.52	1.78	1.13	5.66	7.71	14.12	19.73	28.35
24	16.79	10.21	4.52	1.78	1.14	5.66	7.68	14.10	19.70	28.33
25	16.79	10.21	4.53	1.79	1.15	5.65	7.64	14.09	19.68	28.27
26	16.80	10.21	4.54	1.80	1.16	5.64	7.63	14.08	19.66	28.25
27	16.83	10.21	4.55	1.81	1.17	5.61	7.62	14.06	19.64	28.24
28	16.83	10.23	4.56	1.81	1.18	5.60	7.61	14.05	19.64	28.23
29	16.83	10.24	4.57	1.83	1.19	5.59	7.60	14.04	19.64	28.23
30	16.85	10.25	4.57	1.84	1.19	5.58	7.60	14.04	19.62	28.21
31	16.87	10.27	4.57	1.85	1.20	5.56	7.59	14.04	19.62	28.20
32	16.90	10.28	4.57	1.85	1.20	5.54	7.58	14.03	19.60	28.20
33	16.90	10.28	4.58	1.87	1.21	5.53	7.56	14.02	19.60	28.19
34	16.92	10.29	4.58	1.87	1.21	5.51	7.55	14.01	19.59	28.18
35	16.93	10.30	4.59	1.88	1.22	5.50	7.53	14.00	19.58	28.17
36	16.93	10.31	4.59	1.89	1.23	5.49	7.52	14.00	19.57	28.16
37	16.94	10.33	4.60	1.90	1.24	5.48	7.51	14.00	19.56	28.16
38	16.94	10.34	4.60	1.91	1.25	5.47	7.50	14.00	19.56	28.14
39	16.94	10.35	4.61	1.92	1.26	5.47	7.49	13.99	19.55	28.13
40	16.95	10.36	4.61	1.93	1.28	5.45	7.48	13.98	19.53	28.12

Table F-6: Shear modulus and damping ratio values for Test Pit 4 under axial stress of 400 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	19.51	13.06	7.87	4.44	1.20	4.73	7.54	10.07	16.87	20.48
2	19.82	13.34	8.20	4.97	1.80	4.58	7.35	9.98	16.42	20.20
3	19.97	13.70	8.29	5.14	1.97	4.56	7.05	9.97	16.47	20.12
4	20.08	13.93	8.39	5.17	2.11	4.48	7.03	9.89	16.45	19.90
5	20.21	14.08	8.44	5.18	2.18	4.26	7.03	9.86	16.43	19.77
6	20.23	14.14	8.38	5.19	2.21	4.22	6.99	9.81	16.43	19.31
7	20.25	14.19	8.46	5.19	2.24	4.17	7.00	9.68	16.41	19.21
8	20.26	14.19	8.46	5.19	2.33	4.19	6.98	9.52	16.41	19.07
9	20.32	14.20	8.49	5.25	2.34	4.14	6.98	9.35	16.40	19.04
10	20.35	14.27	8.57	5.26	2.34	4.48	6.97	9.33	16.41	19.07
11	20.40	14.29	8.57	5.30	2.34	4.26	6.96	9.16	16.41	19.04
12	20.42	14.33	8.56	5.31	2.34	4.22	6.96	9.10	16.39	18.97
13	20.48	14.33	8.57	5.31	2.35	4.17	6.92	9.02	16.40	19.01
14	20.48	14.34	8.57	5.33	2.38	4.19	6.93	8.97	16.43	18.81
15	20.54	14.36	8.57	5.34	2.39	4.14	6.91	8.91	16.39	18.68
16	20.54	14.38	8.58	5.38	2.39	4.14	6.90	8.81	16.39	18.69
17	20.54	14.39	8.60	5.43	2.40	4.12	6.89	8.72	16.38	18.69
18	20.56	14.42	8.61	5.44	2.40	4.07	6.83	8.71	16.37	18.68
19	20.59	14.43	8.64	5.44	2.43	4.07	6.78	8.64	16.37	18.68
20	20.61	14.52	8.73	5.46	2.43	4.04	6.68	8.63	16.32	18.63
21	20.62	14.56	8.75	5.47	2.43	4.03	6.67	8.61	16.17	18.57
22	20.62	14.58	8.76	5.48	2.43	4.03	6.60	8.60	16.15	18.38
23	20.64	14.59	8.77	5.48	2.44	3.99	6.57	8.62	16.10	18.38
24	20.66	14.64	8.77	5.49	2.45	4.01	6.54	8.59	16.06	18.33
25	20.68	14.66	8.83	5.49	2.46	3.97	6.52	8.58	16.05	18.16
26	20.68	14.66	8.85	5.50	2.46	3.98	6.52	8.58	16.07	18.12
27	20.68	14.67	8.92	5.50	2.46	3.99	6.54	8.52	16.05	18.11
28	20.69	14.69	8.95	5.50	2.47	3.95	6.49	8.54	16.00	18.12
29	20.70	14.73	9.02	5.51	2.47	3.94	6.48	8.50	16.00	18.12
30	20.74	14.74	9.01	5.51	2.47	3.90	6.46	8.45	15.98	18.11
31	20.77	14.76	9.00	5.53	2.48	3.90	6.46	8.43	15.97	18.07
32	20.79	14.79	8.98	5.54	2.48	3.90	6.46	8.47	15.96	18.09
33	20.80	14.80	8.98	5.55	2.48	3.86	6.44	8.40	15.95	18.06
34	20.84	14.81	8.97	5.56	2.49	3.85	6.41	8.38	15.88	18.03
35	20.85	14.82	8.96	5.57	2.49	3.87	6.41	8.47	15.83	18.04
36	20.90	14.83	8.96	5.57	2.50	3.89	6.39	8.40	15.74	18.04
37	20.90	14.83	8.95	5.57	2.50	3.85	6.34	8.38	15.63	18.02
38	20.93	14.84	8.94	5.58	2.51	3.83	6.34	8.39	15.50	18.02
39	20.94	14.85	8.94	5.59	2.52	3.80	6.32	8.39	15.38	18.00
40	20.96	14.85	8.93	5.59	2.52	3.70	6.30	8.33	15.38	17.99

Table F-7: Shear modulus and damping ratio values for Test Pit 6 under axial stress of 100 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	18.65	13.79	5.66	3.90	2.75	5.61	9.06	12.88	22.70	29.34
2	18.84	13.87	5.70	3.94	2.95	5.59	8.95	12.74	22.67	29.14
3	19.00	14.02	5.88	4.12	3.04	5.48	8.85	12.63	22.61	29.04
4	19.11	14.02	5.99	4.23	3.12	5.38	8.66	12.61	22.55	28.74
5	19.16	14.02	6.02	4.25	3.19	5.32	8.50	12.52	22.53	27.88
6	19.23	14.04	6.04	4.28	3.19	5.28	8.37	11.75	22.28	27.54
7	19.24	14.04	6.04	4.28	3.19	5.27	8.36	11.29	21.82	27.43
8	19.25	14.04	6.05	4.30	3.20	5.26	8.35	11.24	21.68	27.39
9	19.27	14.04	6.08	4.34	3.32	5.24	8.31	11.22	21.02	27.24
10	19.27	14.05	6.10	4.36	3.32	5.24	8.31	11.20	20.85	27.23
11	19.28	14.05	6.12	4.37	3.32	5.23	8.29	11.17	20.83	27.23
12	19.30	14.06	6.14	4.40	3.32	5.21	8.28	11.10	20.83	27.23
13	19.30	14.07	6.14	4.40	3.32	5.20	8.27	11.10	20.80	27.04
14	19.33	14.07	6.16	4.40	3.32	5.19	8.26	11.08	20.73	26.92
15	19.38	14.08	6.16	4.41	3.32	5.19	8.24	10.98	20.73	26.75
16	19.40	14.09	6.18	4.41	3.34	5.18	8.22	10.96	20.59	26.65
17	19.40	14.11	6.18	4.41	3.36	5.17	8.21	10.94	20.57	26.51
18	19.42	14.13	6.20	4.41	3.36	5.16	8.19	10.94	20.56	25.98
19	19.42	14.13	6.21	4.41	3.36	5.15	8.17	10.93	20.53	25.90
20	19.44	14.14	6.22	4.41	3.38	5.13	8.15	10.88	20.53	25.85
21	19.45	14.15	6.22	4.41	3.38	5.11	8.13	10.81	20.53	25.81
22	19.46	14.15	6.22	4.41	3.38	5.10	8.11	10.80	20.53	25.74
23	19.54	14.15	6.23	4.42	3.40	5.10	8.10	10.78	20.53	25.67
24	19.54	14.16	6.24	4.42	3.40	5.09	8.10	10.76	20.53	25.64
25	19.56	14.18	6.28	4.42	3.40	5.08	8.08	10.75	20.27	25.63
26	19.60	14.19	6.28	4.42	3.40	5.05	8.07	10.72	20.27	25.60
27	19.70	14.19	6.32	4.42	3.40	5.04	7.96	10.69	20.27	25.58
28	19.71	14.19	6.32	4.42	3.40	5.03	7.93	10.68	20.26	25.54
29	19.72	14.19	6.32	4.43	3.40	5.02	7.90	10.64	20.26	25.44
30	19.73	14.19	6.32	4.43	3.41	5.01	7.89	10.63	20.25	25.40
31	19.76	14.20	6.37	4.43	3.44	4.99	7.88	10.62	20.24	25.34
32	19.77	14.20	6.37	4.43	3.44	4.98	7.86	10.59	20.24	25.34
33	19.82	14.21	6.37	4.43	3.44	4.97	7.85	10.55	20.24	25.30
34	19.82	14.23	6.38	4.43	3.44	4.96	7.84	10.55	20.13	25.30
35	19.82	14.26	6.38	4.44	3.44	4.95	7.83	10.49	19.83	25.30
36	19.83	14.32	6.38	4.44	3.45	4.95	7.82	10.44	19.61	25.30
37	19.83	14.37	6.38	4.44	3.45	4.94	7.82	10.44	19.57	25.20
38	19.84	14.43	6.45	4.45	3.45	4.94	7.81	10.15	19.50	25.20
39	19.84	14.46	6.48	4.46	3.46	4.93	7.81	10.11	19.49	25.20
40	19.85	14.47	6.49	4.47	3.47	4.93	7.80	10.11	19.48	25.19

Table F-8: Shear modulus and damping ratio values for Test Pit 6 under axial stress of 200 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	20.98	15.11	8.81	5.33	3.92	4.37	6.88	10.80	18.22	26.47
2	20.98	15.12	8.81	5.38	3.94	4.24	6.81	10.76	18.02	27.45
3	21.01	15.41	8.83	5.41	4.06	4.15	6.75	10.64	17.95	27.27
4	21.09	15.48	8.83	5.53	4.19	4.12	6.67	10.57	17.81	27.25
5	21.19	16.10	9.70	5.57	4.23	4.06	5.55	9.89	16.67	27.15
6	21.20	16.15	9.73	5.61	4.26	4.03	5.30	9.88	16.65	27.10
7	21.25	16.18	9.76	5.66	4.34	3.99	5.30	9.86	16.63	27.10
8	21.29	16.25	9.80	5.69	4.38	3.98	5.29	9.84	16.60	27.06
9	21.30	16.25	9.82	5.70	4.40	3.97	5.28	9.82	16.58	27.00
10	21.35	16.26	9.89	5.72	4.42	3.96	5.27	9.80	16.57	26.99
11	21.36	16.27	9.90	5.72	4.44	3.95	5.25	9.77	16.52	26.92
12	21.36	16.27	9.91	5.75	4.45	3.89	5.24	9.76	16.49	26.82
13	21.39	16.28	9.91	5.75	4.45	3.66	5.21	9.74	16.47	26.82
14	21.43	16.28	9.92	5.77	4.46	3.32	5.21	9.71	16.45	26.68
15	21.43	16.28	9.92	5.78	4.47	3.09	5.17	9.68	16.43	26.55
16	21.46	16.28	9.93	5.79	4.49	3.04	5.15	9.67	16.40	26.51
17	21.46	16.29	9.94	5.80	4.50	3.02	5.11	9.66	16.39	26.49
18	21.47	16.29	9.95	5.82	4.52	3.01	5.08	9.66	16.37	26.46
19	21.49	16.29	9.96	5.84	4.54	2.98	5.05	9.64	16.37	26.39
20	21.49	16.30	9.97	5.85	4.57	2.97	5.03	9.64	16.35	26.39
21	21.50	16.30	9.98	5.85	4.57	2.97	4.96	9.63	16.30	26.28
22	21.53	16.30	9.99	5.86	4.57	2.96	4.94	9.61	16.28	26.27
23	21.53	16.32	10.00	5.87	4.58	2.92	4.88	9.58	16.23	26.26
24	21.53	16.33	10.01	5.88	4.59	2.92	4.84	9.56	16.18	26.24
25	21.55	16.33	10.02	5.89	4.61	2.91	4.80	9.55	16.15	26.14
26	21.57	16.34	10.03	5.90	4.62	2.90	4.79	9.53	16.12	26.11
27	21.58	16.34	10.04	5.91	4.63	2.86	4.78	9.51	16.10	26.10
28	21.60	16.36	10.05	5.91	4.63	2.85	4.76	9.50	16.10	26.08
29	21.61	16.37	10.06	5.93	4.65	2.84	4.75	9.49	16.09	26.08
30	21.62	16.38	10.06	5.94	4.65	2.82	4.75	9.49	16.07	26.05
31	21.63	16.40	10.06	5.95	4.66	2.77	4.74	9.48	16.06	26.04
32	21.63	16.41	10.06	5.96	4.66	2.76	4.73	9.47	16.04	26.03
33	21.64	16.41	10.07	5.98	4.67	2.75	4.71	9.46	16.03	26.02
34	21.65	16.42	10.07	5.98	4.68	2.73	4.70	9.45	16.02	26.01
35	21.65	16.43	10.08	5.99	4.69	2.73	4.67	9.44	16.01	25.99
36	21.66	16.44	10.08	6.00	4.70	2.72	4.66	9.43	15.99	25.98
37	21.66	16.46	10.09	6.01	4.71	2.70	4.65	9.43	15.98	25.97
38	21.66	16.47	10.09	6.02	4.72	2.70	4.64	9.43	15.97	25.95
39	21.67	16.49	10.10	6.03	4.73	2.69	4.63	9.42	15.97	25.94
40	22.16	16.50	10.11	6.04	4.73	2.67	4.62	9.41	15.96	25.94

Table F-9: Shear modulus and damping ratio values for Test Pit 6 under axial stress of 400 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	26.30	18.80	12.01	7.13	5.23	2.31	4.85	7.01	13.77	17.45
2	26.62	19.10	12.38	7.74	5.51	2.09	4.58	6.88	13.21	17.05
3	26.77	19.49	12.48	7.94	5.71	2.06	4.16	6.87	13.18	16.94
4	26.89	19.73	12.58	7.97	5.87	1.95	4.14	6.76	13.15	16.64
5	27.02	19.90	12.60	7.99	5.95	1.95	4.14	6.72	13.15	16.45
6	27.04	19.96	12.65	8.00	5.99	1.65	4.09	6.65	13.15	15.81
7	27.06	20.01	12.67	8.00	6.02	1.65	4.08	6.46	13.14	15.66
8	27.07	20.01	12.68	8.00	6.13	1.59	4.07	6.23	13.12	15.46
9	27.13	20.02	12.71	8.07	6.14	1.59	4.06	5.99	13.12	15.46
10	27.17	20.10	12.79	8.08	6.14	1.54	4.05	5.96	13.12	15.42
11	27.22	20.12	12.80	8.12	6.14	1.54	4.04	5.73	13.12	15.42
12	27.24	20.17	12.80	8.13	6.14	1.52	4.04	5.65	13.11	15.38
13	27.30	20.17	12.80	8.13	6.15	1.52	3.99	5.53	13.11	15.33
14	27.30	20.18	12.80	8.16	6.19	1.48	3.98	5.46	13.10	15.10
15	27.36	20.20	12.80	8.17	6.20	1.48	3.96	5.37	13.10	14.93
16	27.36	20.22	12.81	8.22	6.20	1.48	3.95	5.23	13.10	14.93
17	27.36	20.23	12.83	8.27	6.21	1.44	3.94	5.11	13.08	14.92
18	27.38	20.26	12.84	8.28	6.21	1.38	3.85	5.10	13.07	14.91
19	27.41	20.27	12.88	8.28	6.24	1.38	3.79	5.00	13.06	14.91
20	27.43	20.37	12.98	8.31	6.24	1.34	3.65	4.98	13.00	14.84
21	27.44	20.41	13.00	8.32	6.25	1.32	3.63	4.97	12.78	14.76
22	27.44	20.43	13.01	8.33	6.25	1.32	3.53	4.95	12.76	14.50
23	27.46	20.45	13.02	8.33	6.26	1.29	3.49	4.94	12.68	14.49
24	27.49	20.50	13.03	8.34	6.27	1.26	3.45	4.93	12.65	14.42
25	27.51	20.52	13.09	8.34	6.28	1.26	3.44	4.91	12.63	14.19
26	27.51	20.52	13.11	8.35	6.28	1.25	3.42	4.91	12.62	14.13
27	27.51	20.53	13.19	8.35	6.28	1.24	3.42	4.85	12.61	14.12
28	27.52	20.55	13.21	8.35	6.29	1.21	3.38	4.83	12.54	14.12
29	27.53	20.60	13.22	8.36	6.29	1.19	3.36	4.80	12.54	14.11
30	27.57	20.61	13.22	8.36	6.29	1.13	3.34	4.76	12.51	14.11
31	27.60	20.63	13.23	8.39	6.30	1.13	3.34	4.76	12.50	14.08
32	27.62	20.66	13.23	8.40	6.30	1.13	3.33	4.73	12.49	14.05
33	27.63	20.67	13.24	8.41	6.30	1.12	3.31	4.70	12.47	14.04
34	27.67	20.68	13.24	8.42	6.32	1.09	3.26	4.66	12.37	14.02
35	27.68	20.69	13.25	8.43	6.32	1.08	3.26	4.66	12.30	14.02
36	27.73	20.70	13.26	8.43	6.33	1.06	3.23	4.65	12.18	14.00
37	27.73	20.70	13.26	8.44	6.33	1.06	3.17	4.65	12.02	13.98
38	27.76	20.72	13.28	8.45	6.34	1.04	3.17	4.63	11.84	13.98
39	27.77	20.73	13.30	8.46	6.35	1.00	3.13	4.63	11.67	13.96
40	27.79	20.73	13.31	8.46	6.35	0.85	3.11	4.56	11.67	13.95

Table F-10: Shear modulus and damping ratio values for Test Pit 7 under axial stress of 100 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	15.35	9.85	2.54	1.07	0.30	8.45	11.66	14.16	24.73	29.92
2	15.63	10.04	2.66	1.17	0.39	8.37	11.57	15.47	24.71	29.60
3	15.81	10.11	2.69	1.20	0.50	8.36	11.50	15.38	24.65	29.46
4	15.96	10.24	2.82	1.31	0.55	8.28	11.43	15.30	24.60	29.40
5	16.07	10.38	2.90	1.38	0.59	8.22	11.30	15.23	24.69	28.82
6	16.11	10.44	2.92	1.39	0.61	8.18	11.20	15.29	24.61	28.62
7	16.18	10.46	2.94	1.41	0.62	8.15	11.11	14.78	24.43	28.40
8	16.19	10.50	2.94	1.41	0.63	8.14	11.10	14.47	24.12	28.32
9	16.22	10.51	2.95	1.42	0.63	8.14	11.10	14.41	24.02	28.30
10	16.23	10.53	2.97	1.45	0.69	8.12	11.07	14.33	23.57	28.19
11	16.23	10.56	2.98	1.46	0.69	8.12	11.07	14.26	23.46	28.19
12	16.25	10.58	3.00	1.46	0.69	8.12	11.06	14.25	23.44	28.20
13	16.26	10.59	3.01	1.48	0.69	8.10	11.05	14.24	23.42	28.18
14	16.27	10.60	3.01	1.50	0.69	8.10	11.04	14.23	23.44	28.06
15	16.29	10.63	3.03	1.50	0.70	8.09	11.04	14.04	23.38	27.98
16	16.36	10.63	3.03	1.51	0.72	8.09	11.02	14.09	23.38	27.87
17	16.39	10.64	3.04	1.56	0.73	8.08	11.01	14.01	23.28	27.80
18	16.40	10.66	3.04	1.51	0.76	8.08	11.00	14.17	23.27	27.71
19	16.40	10.67	3.06	1.52	0.78	8.07	10.99	14.08	23.26	27.36
20	16.41	10.68	3.06	1.53	0.82	8.06	10.98	14.08	23.24	27.30
21	16.43	10.68	3.07	1.52	0.82	8.05	10.96	14.03	23.19	27.27
22	16.47	10.71	3.07	1.54	0.83	8.04	10.95	14.02	23.17	27.24
23	16.47	10.72	3.07	1.53	0.84	8.03	10.94	13.97	23.17	27.20
24	16.49	10.74	3.08	1.57	0.85	8.03	10.93	14.00	23.13	27.15
25	16.49	10.74	3.08	1.59	0.85	8.02	10.93	14.08	23.10	27.13
26	16.51	10.76	3.11	1.61	0.87	8.02	10.92	14.04	23.06	27.12
27	16.53	10.78	3.11	1.61	0.89	8.00	10.91	14.03	23.06	27.10
28	16.62	10.79	3.14	1.64	0.89	7.99	10.84	14.02	23.05	27.06
29	16.63	10.80	3.14	1.65	0.90	7.98	10.82	13.97	23.04	27.00
30	16.64	10.81	3.14	1.66	0.92	7.96	10.80	14.00	23.06	26.97
31	16.65	10.83	3.14	1.68	0.93	7.97	10.79	13.98	23.04	26.97
32	16.68	10.85	3.18	1.69	0.94	7.96	10.78	13.94	23.06	26.93
33	16.69	10.86	3.18	1.72	0.94	7.95	10.77	13.90	23.06	26.90
34	16.72	10.86	3.18	1.72	0.95	7.94	10.76	13.90	23.04	26.91
35	16.72	10.87	3.19	1.73	0.93	7.94	10.76	13.50	22.97	26.88
36	16.73	10.88	3.19	1.75	0.96	7.93	10.75	13.48	22.76	26.86
37	16.73	10.88	3.19	1.78	0.98	7.93	10.75	13.56	22.62	26.84
38	16.74	10.89	3.19	1.79	0.99	7.92	10.74	13.58	22.59	26.83
39	16.75	10.90	3.24	1.80	0.99	7.92	10.73	13.61	22.54	26.82
40	16.76	10.92	3.26	1.81	1.01	7.92	10.72	13.68	22.53	26.81

Table F-11: Shear modulus and damping ratio values for Test Pit7 under axial stress of 200 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	17.97	10.53	5.71	1.84	0.68	6.85	8.55	12.01	18.88	26.41
2	18.01	10.54	5.78	1.90	0.70	6.74	8.50	11.98	18.84	26.37
3	18.11	10.85	5.88	1.94	0.84	6.67	8.45	11.88	18.80	26.32
4	18.61	10.92	5.99	2.09	0.97	6.64	8.38	11.82	18.71	26.30
5	18.70	11.59	6.08	2.14	1.01	6.59	7.49	11.26	18.03	26.28
6	18.90	11.64	6.11	2.19	1.04	6.57	7.29	11.25	18.02	26.26
7	18.90	11.68	6.15	2.25	1.12	6.53	7.29	11.24	18.01	26.25
8	18.94	11.75	6.20	2.28	1.17	6.53	7.28	11.22	17.99	26.14
9	19.03	11.75	6.23	2.30	1.19	6.52	7.27	11.21	17.98	26.13
10	19.14	11.76	6.32	2.32	1.20	6.50	7.26	11.19	17.98	26.04
11	19.15	11.77	6.33	2.32	1.23	6.51	7.25	11.16	17.95	26.01
12	19.20	11.77	6.34	2.36	1.24	6.45	7.24	11.16	17.93	25.98
13	19.24	11.78	6.34	2.36	1.24	6.26	7.21	11.14	17.92	25.98
14	19.26	11.78	6.35	2.38	1.25	5.99	7.21	11.12	17.90	25.87
15	19.32	11.78	6.36	2.39	1.26	5.66	7.18	11.09	17.89	25.79
16	19.33	11.78	6.37	2.41	1.28	5.79	7.17	11.08	17.87	25.71
17	19.33	11.80	6.38	2.42	1.29	5.71	7.13	11.07	17.87	25.68
18	19.36	11.80	6.39	2.44	1.31	5.75	7.11	11.07	17.86	25.66
19	19.41	11.80	6.41	2.47	1.33	5.74	7.09	11.06	17.86	25.61
20	19.41	11.81	6.42	2.48	1.37	5.73	7.07	11.05	17.84	25.61
21	19.44	11.81	6.43	2.48	1.37	5.70	7.01	11.03	17.81	25.55
22	19.45	11.81	6.44	2.49	1.38	5.70	7.00	11.03	17.80	25.55
23	19.45	11.83	6.46	2.50	1.38	5.69	6.95	11.01	17.77	25.54
24	19.47	11.84	6.47	2.52	1.39	5.66	6.92	10.99	17.74	25.53
25	19.48	11.84	6.48	2.53	1.41	5.65	6.89	10.98	17.73	25.47
26	19.49	11.85	6.49	2.54	1.42	5.64	6.88	10.97	17.71	25.45
27	19.50	11.85	6.51	2.55	1.43	5.61	6.87	10.95	17.70	25.44
28	19.52	11.87	6.52	2.55	1.44	5.60	6.85	10.94	17.70	25.43
29	19.53	11.88	6.53	2.58	1.45	5.59	6.85	10.93	17.69	25.43
30	19.55	11.89	6.53	2.59	1.45	5.58	6.85	10.93	17.68	25.41
31	19.57	11.91	6.53	2.60	1.46	5.53	6.84	10.93	17.67	25.41
32	19.60	11.92	6.53	2.61	1.46	5.53	6.83	10.92	17.66	25.40
33	19.61	11.92	6.55	2.64	1.48	5.52	6.81	10.91	17.65	25.40
34	19.62	11.94	6.55	2.64	1.48	5.50	6.81	10.90	17.65	25.39
35	19.63	11.95	6.56	2.65	1.49	5.50	6.78	10.89	17.64	25.38
36	19.64	11.96	6.56	2.66	1.50	5.49	6.77	10.89	17.63	25.37
37	19.65	11.98	6.57	2.68	1.51	5.48	6.76	10.89	17.62	25.37
38	19.65	11.99	6.57	2.69	1.52	5.48	6.76	10.89	17.62	25.35
39	19.65	12.01	6.59	2.70	1.53	5.47	6.75	10.88	17.61	25.34
40	19.66	12.02	6.60	2.72	1.56	5.45	6.74	10.87	17.59	25.33

Table F-12: Shear modulus and damping ratio values for Test Pit7 under axial stress of 400 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	22.63	15.15	11.25	6.26	1.46	4.19	6.79	6.98	14.95	18.45
2	22.99	15.48	11.72	7.00	2.20	4.12	6.62	6.89	14.80	18.19
3	23.16	15.90	11.85	7.25	2.40	4.10	6.35	6.88	14.84	18.12
4	23.30	16.15	12.00	7.29	2.57	4.03	6.34	6.80	14.82	17.93
5	23.44	16.34	12.07	7.31	2.66	3.84	6.34	6.77	14.80	17.81
6	23.47	16.40	11.98	7.32	2.70	3.80	6.30	6.72	14.80	17.40
7	23.49	16.46	12.09	7.32	2.73	3.76	6.30	6.59	14.78	17.30
8	23.50	16.46	12.10	7.32	2.84	3.77	6.28	6.43	14.78	17.18
9	23.57	16.47	12.14	7.41	2.85	3.73	6.29	6.26	14.78	17.15
10	23.61	16.55	12.26	7.42	2.85	4.03	6.28	6.24	14.78	17.18
11	23.67	16.57	12.26	7.47	2.85	3.84	6.27	6.07	14.78	17.15
12	23.69	16.63	12.24	7.48	2.86	3.80	6.27	6.01	14.77	17.09
13	23.76	16.63	12.26	7.48	2.86	3.76	6.23	5.93	14.78	17.13
14	23.76	16.64	12.26	7.52	2.91	3.77	6.24	5.88	14.80	16.95
15	23.83	16.66	12.26	7.53	2.92	3.73	6.22	5.82	14.77	16.83
16	23.83	16.68	12.27	7.59	2.92	3.73	6.21	5.72	14.77	16.84
17	23.83	16.69	12.29	7.65	2.93	3.71	6.21	5.63	14.76	16.84
18	23.85	16.72	12.31	7.66	2.93	3.67	6.15	5.62	14.74	16.83
19	23.88	16.74	12.36	7.66	2.96	3.67	6.11	5.55	14.75	16.83
20	23.90	16.84	12.48	7.70	2.96	3.64	6.02	5.54	14.71	16.78
21	23.91	16.89	12.51	7.71	2.97	3.63	6.01	5.52	14.57	16.73
22	23.91	16.91	12.52	7.73	2.97	3.63	5.95	5.51	14.55	16.56
23	23.94	16.93	12.54	7.73	2.98	3.59	5.92	5.53	14.50	16.56
24	23.97	16.98	12.55	7.74	2.99	3.61	5.89	5.50	14.47	16.51
25	23.99	17.00	12.62	7.74	3.00	3.58	5.88	5.49	14.46	16.36
26	23.99	17.00	12.65	7.75	3.00	3.59	5.88	5.49	14.48	16.32
27	23.99	17.01	12.75	7.75	3.00	3.59	5.89	5.43	14.46	16.31
28	24.00	17.04	12.80	7.75	3.01	3.56	5.85	5.45	14.41	16.32
29	24.02	17.09	12.90	7.76	3.01	3.55	5.84	5.41	14.41	16.33
30	24.06	17.10	12.89	7.76	3.01	3.51	5.82	5.36	14.39	16.31
31	24.09	17.12	12.86	7.80	3.02	3.51	5.82	5.34	14.39	16.28
32	24.12	17.15	12.84	7.81	3.02	3.51	5.82	5.38	14.38	16.29
33	24.13	17.17	12.84	7.82	3.02	3.48	5.80	5.31	14.37	16.27
34	24.17	17.18	12.83	7.84	3.04	3.46	5.77	5.29	14.30	16.24
35	24.18	17.19	12.81	7.85	3.04	3.48	5.77	5.38	14.26	16.26
36	24.24	17.20	12.81	7.85	3.05	3.50	5.75	5.31	14.18	16.26
37	24.24	17.20	12.80	7.86	3.05	3.46	5.72	5.29	14.08	16.23
38	24.27	17.22	12.79	7.87	3.06	3.45	5.72	5.30	13.96	16.23
39	24.29	17.23	12.79	7.88	3.07	3.43	5.69	5.30	13.86	16.22
40	24.31	17.23	12.78	7.88	3.07	3.33	5.68	5.24	13.86	16.21

Table F-13: Shear modulus and damping ratio values for Test Pit 8 under axial stress of 100 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	18.04	12.22	4.39	2.39	2.24	5.95	9.40	13.22	23.04	29.68
2	18.23	12.30	4.43	3.43	2.44	5.93	9.29	13.08	23.01	29.48
3	18.39	12.45	4.61	3.61	2.53	5.82	9.19	12.97	22.95	29.38
4	18.50	12.45	4.72	3.72	2.61	5.72	9.00	12.95	22.89	29.08
5	18.55	12.45	4.75	3.74	2.68	5.66	8.84	12.86	22.87	28.22
6	18.62	12.47	4.77	3.77	2.68	5.62	8.71	12.09	22.62	27.88
7	18.63	12.47	4.77	3.77	2.68	5.61	8.70	11.63	22.16	27.77
8	18.64	12.47	4.78	3.79	2.69	5.60	8.69	11.58	22.02	27.73
9	18.66	12.47	4.81	3.83	2.70	5.58	8.65	11.56	21.36	27.58
10	18.66	12.48	4.83	3.85	2.74	5.58	8.65	11.54	21.19	27.57
11	18.67	12.48	4.85	3.86	2.76	5.57	8.63	11.51	21.17	27.57
12	18.69	12.49	4.87	3.89	2.79	5.55	8.62	11.44	21.17	27.57
13	18.69	12.50	4.87	3.91	2.79	5.54	8.61	11.44	21.14	27.38
14	18.72	12.50	4.89	3.93	2.80	5.53	8.60	11.42	21.07	27.26
15	18.77	12.51	4.89	3.93	2.81	5.53	8.58	11.32	21.07	27.09
16	18.79	12.52	4.91	3.95	2.83	5.52	8.56	11.30	20.93	26.99
17	18.80	12.54	4.91	3.90	2.85	5.51	8.55	11.28	20.91	26.85
18	18.81	12.56	4.93	3.95	2.85	5.50	8.53	11.28	20.90	26.32
19	18.81	12.56	4.94	3.97	2.85	5.49	8.51	11.27	20.87	26.24
20	18.83	12.57	4.95	4.01	2.87	5.47	8.49	11.22	20.87	26.19
21	18.84	12.58	4.95	4.03	2.87	5.45	8.47	11.15	20.84	26.15
22	18.85	12.58	4.95	4.04	2.87	5.44	8.45	11.14	20.78	26.08
23	18.93	12.58	4.96	4.05	2.91	5.44	8.44	11.12	20.70	26.01
24	18.93	12.59	4.97	4.07	2.95	5.43	8.44	11.10	20.68	25.98
25	18.95	12.61	5.01	4.08	3.00	5.42	8.42	11.09	20.65	25.97
26	18.99	12.62	5.01	4.08	3.04	5.39	8.41	11.06	20.63	25.94
27	19.09	12.64	5.03	4.09	3.08	5.38	8.30	11.03	20.61	25.92
28	19.10	12.64	5.04	4.10	3.12	5.37	8.27	11.02	20.60	25.88
29	19.11	12.67	5.05	4.11	3.17	5.36	8.24	10.98	20.60	25.78
30	19.12	12.68	5.06	4.13	3.18	5.35	8.23	10.97	20.59	25.74
31	19.15	12.71	5.07	4.15	3.19	5.33	8.22	10.96	20.52	25.68
32	19.16	12.74	5.08	4.18	3.20	5.32	8.20	10.93	20.50	25.68
33	19.18	12.75	5.10	4.20	3.22	5.31	8.19	10.89	20.49	25.64
34	19.19	12.78	5.11	4.22	3.23	5.30	8.18	10.89	20.47	25.62
35	19.21	12.80	5.12	4.24	3.24	5.29	8.17	10.83	20.17	25.61
36	19.22	12.84	5.13	4.27	3.25	5.29	8.16	10.78	19.95	25.60
37	19.22	12.86	5.14	4.29	3.27	5.28	8.16	10.78	19.91	25.59
38	19.23	12.88	5.16	4.31	3.28	5.28	8.15	10.49	19.84	25.58
39	19.24	12.89	5.17	4.33	3.29	5.27	8.15	10.45	19.83	25.57
40	19.25	12.90	5.18	4.36	3.30	5.27	8.14	10.45	19.82	25.56

Table F-14: Shear modulus and damping ratio values for Test Pit 8 under axial stress of 200 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	20.16	13.69	7.54	3.87	2.43	4.73	7.24	11.16	18.58	26.83
2	20.16	13.70	7.55	3.92	2.45	4.60	7.17	11.12	18.38	27.81
3	20.19	13.99	7.56	3.95	2.57	4.51	7.11	11.00	18.31	27.63
4	20.27	14.06	7.57	4.07	2.70	4.48	7.03	10.93	18.17	27.61
5	20.37	14.68	8.44	4.11	2.74	4.42	5.91	10.25	17.03	27.51
6	20.38	14.73	8.47	4.15	2.77	4.39	5.66	10.24	17.01	27.46
7	20.43	14.76	8.50	4.20	2.85	4.35	5.66	10.22	16.99	27.46
8	20.47	14.83	8.54	4.23	2.89	4.34	5.65	10.20	16.96	27.42
9	20.48	14.83	8.56	4.24	2.91	4.33	5.64	10.18	16.94	27.36
10	20.53	14.84	8.63	4.26	2.93	4.32	5.63	10.16	16.93	27.35
11	20.54	14.85	8.64	4.26	2.95	4.31	5.61	10.13	16.88	27.28
12	20.55	14.85	8.65	4.29	2.96	4.25	5.60	10.12	16.85	27.18
13	20.57	14.86	8.65	4.29	2.96	4.02	5.57	10.10	16.83	27.18
14	20.61	14.86	8.65	4.31	2.97	3.68	5.57	10.07	16.81	27.04
15	20.61	14.86	8.66	4.32	2.98	3.45	5.53	10.04	16.79	26.91
16	20.64	14.86	8.67	4.33	3.00	3.40	5.51	10.03	16.76	26.87
17	20.65	14.87	8.68	4.34	3.01	3.38	5.47	10.02	16.75	26.85
18	20.65	14.87	8.69	4.36	3.03	3.37	5.44	10.02	16.73	26.82
19	20.67	14.87	8.70	4.38	3.05	3.34	5.41	10.00	16.73	26.75
20	20.67	14.88	8.71	4.39	3.08	3.33	5.39	10.00	16.71	26.75
21	20.68	14.88	8.72	4.39	3.08	3.33	5.32	9.99	16.66	26.64
22	20.71	14.88	8.73	4.40	3.08	3.32	5.30	9.97	16.64	26.63
23	20.71	14.90	8.74	4.41	3.09	3.28	5.24	9.94	16.59	26.62
24	20.72	14.91	8.75	4.42	3.10	3.28	5.20	9.92	16.54	26.60
25	20.73	14.91	8.76	4.43	3.12	3.27	5.16	9.91	16.51	26.50
26	20.75	14.92	8.77	4.44	3.13	3.26	5.15	9.89	16.48	26.47
27	20.76	14.92	8.78	4.45	3.14	3.22	5.14	9.87	16.46	26.46
28	20.78	14.94	8.79	4.45	3.14	3.21	5.12	9.86	16.46	26.44
29	20.79	14.95	8.80	4.47	3.16	3.20	5.11	9.85	16.45	26.44
30	20.80	14.96	8.81	4.48	3.16	3.18	5.11	9.85	16.43	26.41
31	20.81	14.98	8.83	4.49	3.17	3.13	5.10	9.84	16.42	26.40
32	20.82	14.99	8.82	4.50	3.17	3.12	5.09	9.83	16.40	26.39
33	20.83	14.99	8.82	4.52	3.18	3.11	5.07	9.82	16.39	26.38
34	20.83	15.00	8.83	4.52	3.19	3.09	5.06	9.81	16.38	26.37
35	20.83	15.01	8.84	4.53	3.20	3.09	5.03	9.80	16.37	26.35
36	20.84	15.02	8.85	4.54	3.21	3.08	5.02	9.79	16.35	26.34
37	20.84	15.04	8.86	4.55	3.22	3.06	5.01	9.79	16.34	26.33
38	20.84	15.05	8.88	4.56	3.23	3.06	5.00	9.79	16.33	26.31
39	20.85	15.07	8.89	4.57	3.24	3.05	4.99	9.78	16.33	26.30
40	21.34	15.08	8.90	4.58	3.24	3.03	4.98	9.77	16.32	26.30

Table F-15: Shear modulus and damping ratio values for Test Pit 8 under axial stress of 400 kPa

strain level	0.01%	0.1%	1%	2.5%	5%	0.01%	0.1%	1%	2.5%	5%
cycles No.	G (MPa)					D (%)				
1	25.88	18.38	11.59	6.71	4.81	2.57	5.11	7.27	14.03	17.71
2	26.20	18.68	11.96	7.32	5.09	2.35	4.84	7.14	13.47	17.31
3	26.35	19.07	12.06	7.52	5.29	2.32	4.42	7.13	13.44	17.20
4	26.47	19.31	12.16	7.55	5.45	2.21	4.40	7.02	13.41	16.90
5	26.60	19.48	12.18	7.57	5.53	2.21	4.40	6.98	13.41	16.71
6	26.62	19.54	12.23	7.58	5.57	1.91	4.35	6.91	13.41	16.07
7	26.64	19.59	12.25	7.58	5.60	1.91	4.34	6.72	13.40	15.92
8	26.65	19.59	12.26	7.58	5.71	1.85	4.33	6.49	13.38	15.72
9	26.71	19.60	12.29	7.65	5.72	1.85	4.32	6.25	13.38	15.72
10	26.75	19.68	12.37	7.66	5.72	1.80	4.31	6.22	13.38	15.68
11	26.80	19.70	12.38	7.70	5.72	1.80	4.30	5.99	13.38	15.68
12	26.82	19.75	12.38	7.71	5.72	1.78	4.30	5.91	13.37	15.64
13	26.88	19.75	12.38	7.71	5.73	1.78	4.25	5.79	13.37	15.59
14	26.88	19.76	12.38	7.74	5.77	1.74	4.24	5.72	13.36	15.36
15	26.94	19.78	12.38	7.75	5.78	1.74	4.22	5.63	13.36	15.19
16	26.94	19.80	12.39	7.80	5.78	1.74	4.21	5.49	13.36	15.19
17	26.94	19.81	12.41	7.85	5.79	1.70	4.20	5.37	13.34	15.18
18	26.96	19.84	12.42	7.86	5.79	1.64	4.11	5.36	13.33	15.17
19	26.99	19.85	12.46	7.86	5.82	1.64	4.05	5.26	13.32	15.17
20	27.01	19.95	12.56	7.89	5.82	1.60	3.91	5.24	13.26	15.10
21	27.02	19.99	12.58	7.90	5.83	1.58	3.89	5.23	13.04	15.02
22	27.02	20.01	12.59	7.91	5.83	1.58	3.79	5.21	13.02	14.76
23	27.04	20.03	12.60	7.91	5.84	1.55	3.75	5.20	12.94	14.75
24	27.07	20.08	12.61	7.92	5.85	1.52	3.71	5.19	12.91	14.68
25	27.09	20.10	12.67	7.92	5.86	1.52	3.70	5.17	12.89	14.45
26	27.09	20.10	12.69	7.93	5.86	1.51	3.68	5.17	12.88	14.39
27	27.09	20.11	12.77	7.93	5.86	1.50	3.68	5.11	12.87	14.38
28	27.10	20.13	12.79	7.93	5.87	1.47	3.64	5.09	12.80	14.38
29	27.11	20.18	12.80	7.94	5.87	1.45	3.62	5.06	12.80	14.37
30	27.15	20.19	12.80	7.94	5.87	1.39	3.60	5.02	12.77	14.37
31	27.18	20.21	12.81	7.97	5.88	1.39	3.60	5.02	12.76	14.34
32	27.20	20.24	12.81	7.98	5.88	1.39	3.59	4.99	12.75	14.31
33	27.21	20.25	12.82	7.99	5.88	1.38	3.57	4.96	12.73	14.30
34	27.25	20.26	12.82	8.00	5.90	1.35	3.52	4.92	12.63	14.28
35	27.26	20.27	12.83	8.01	5.90	1.34	3.52	4.92	12.56	14.28
36	27.31	20.28	12.84	8.01	5.91	1.32	3.49	4.91	12.44	14.26
37	27.31	20.28	12.84	8.02	5.91	1.32	3.43	4.91	12.28	14.24
38	27.34	20.30	12.86	8.03	5.92	1.30	3.43	4.89	12.10	14.24
39	27.35	20.31	12.88	8.04	5.93	1.26	3.39	4.89	11.93	14.22
40	27.37	20.31	12.89	8.04	5.93	1.11	3.37	4.82	11.93	14.21

**Appendix G: Shear modulus and damping ratio curves for selected cycles**

Effective vertical stress,  $\sigma_v=100$  kPa

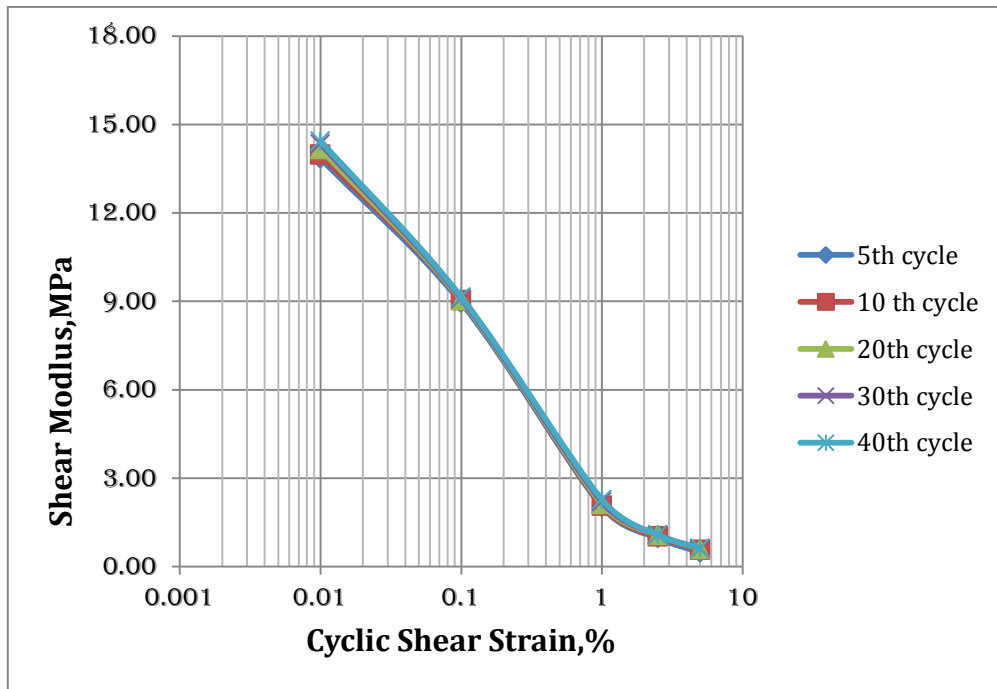


Figure G-1: Shear modulus value for selected cycles, TP 3

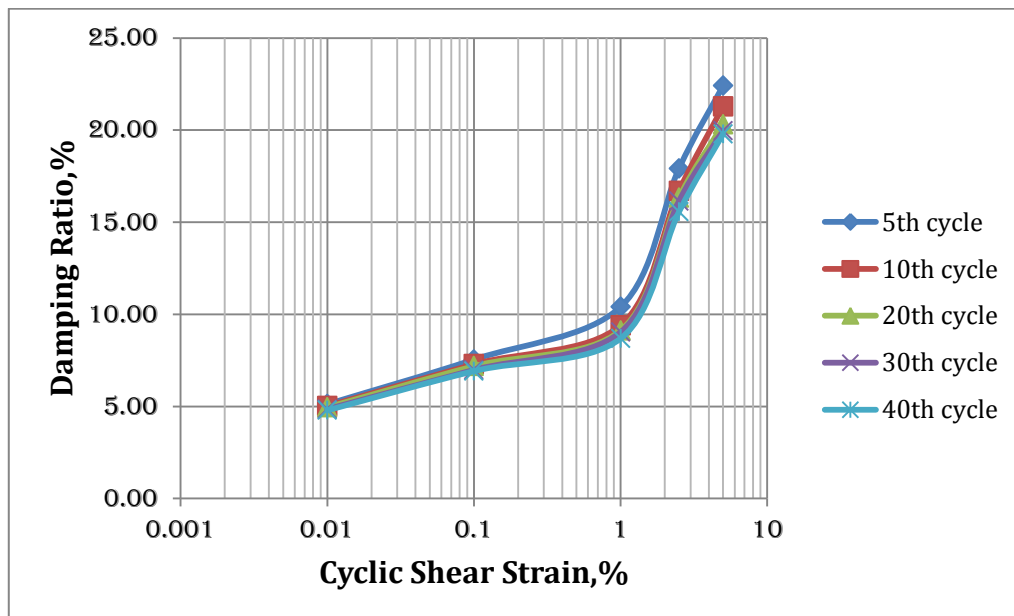


Figure G-2: Damping ratio value for selected cycles, TP 3

Effective vertical stress,  $\sigma_v=200$  kPa

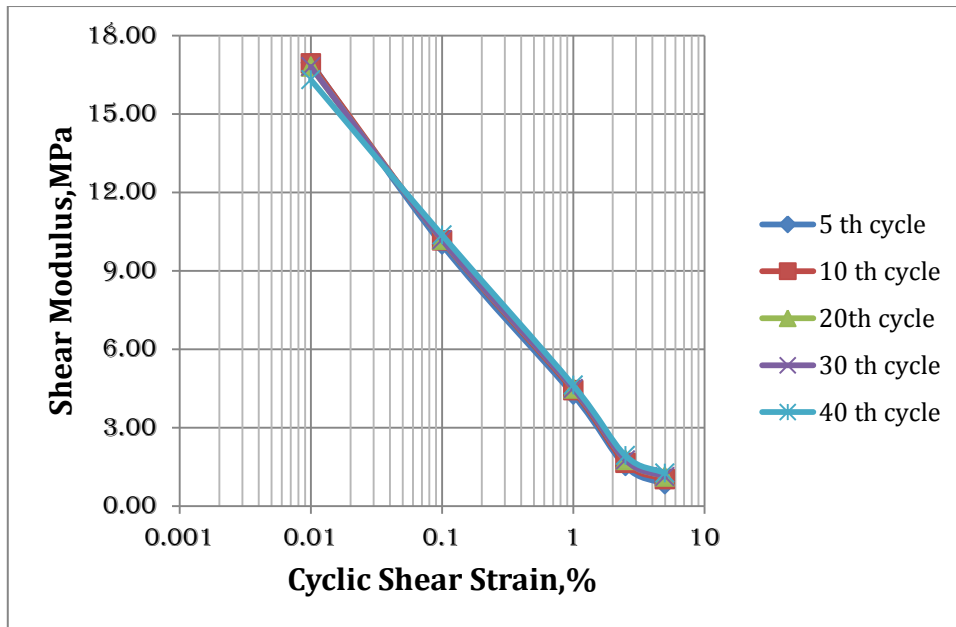


Figure G-3: Shear modulus value for selected cycles, TP 3

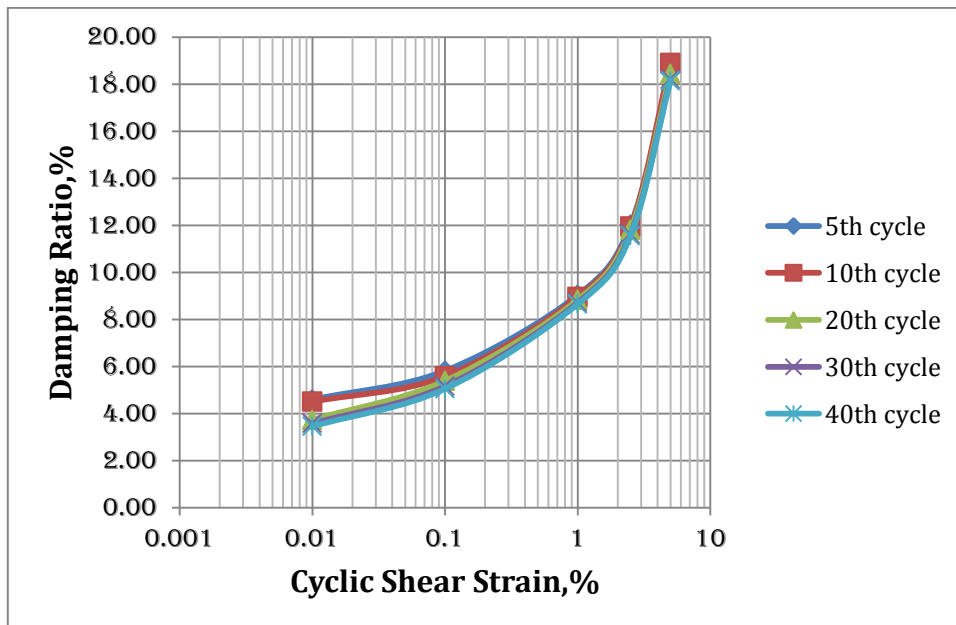


Figure G-4: Damping ratio value for selected cycles, TP 3

Effective vertical stress of  $\sigma_v=400$  kPa

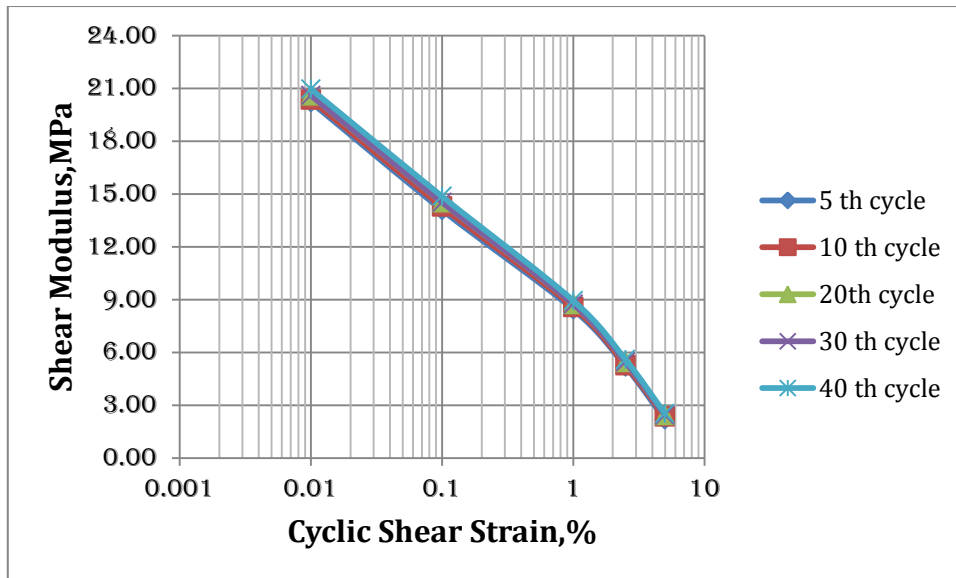


Figure G-5: Shear modulus value for selected cycles, TP 3

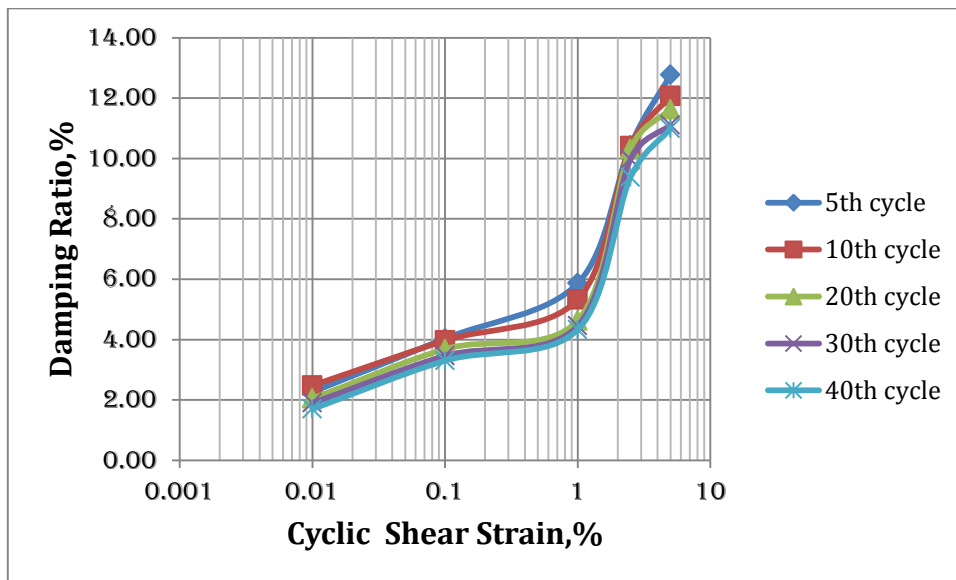


Figure G-6: Damping ratio value for selected cycles, TP 3

**Appendix H: Effect of number of cycles on shear modulus and damping ratio values**

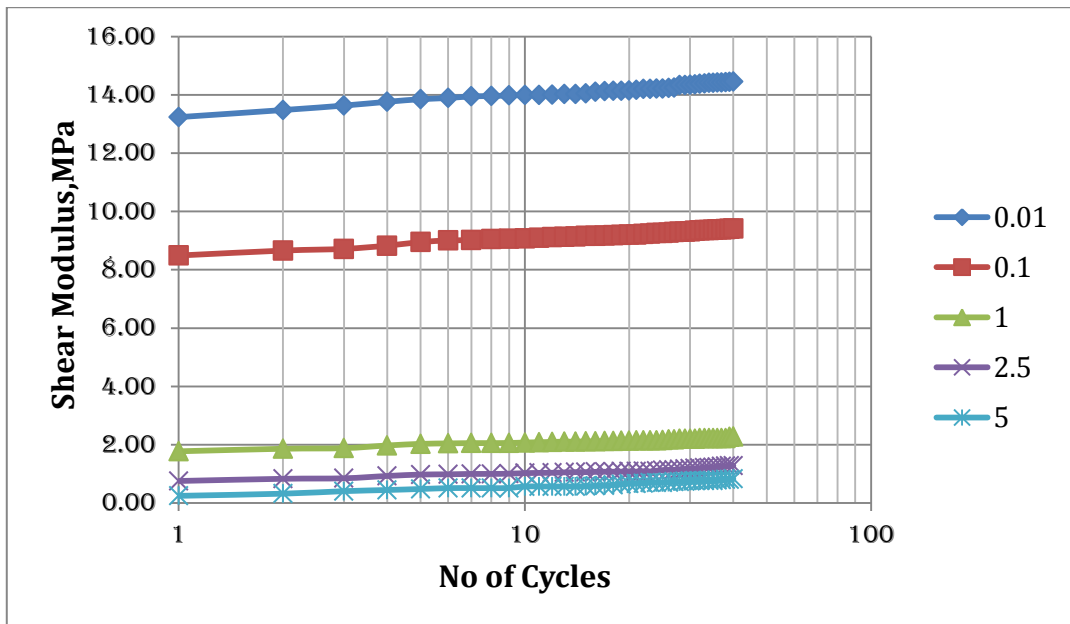


Figure H-1: Effect of number of cycles on shear modulus value for Test Pit 4 under axial stress of 100 kPa

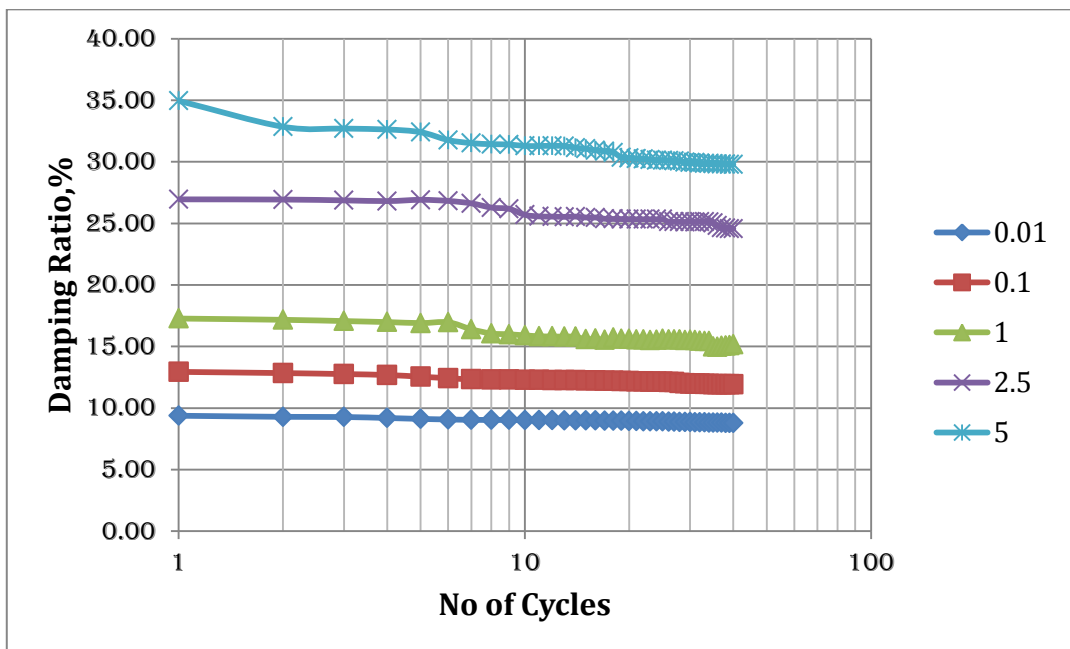


Figure H-2: Effect of number of cycles on damping ratio value for Test Pit 4 under axial stress of 100 kPa

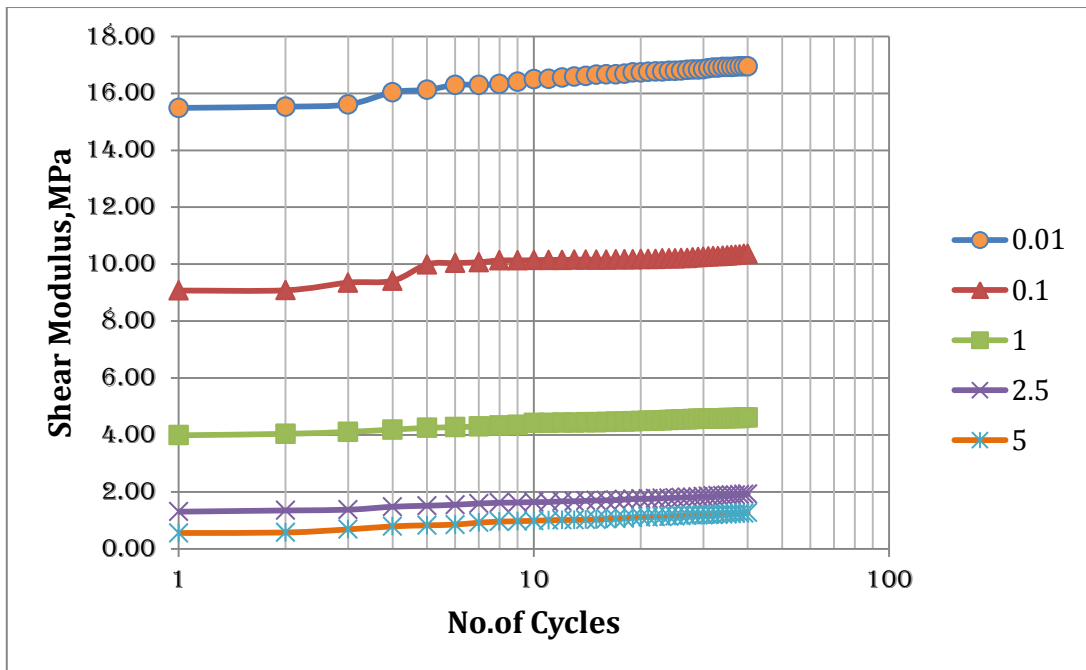


Figure H-3: Effect of number of cycles on shear modulus value for Test Pit 4 under axial stress of 200 kPa

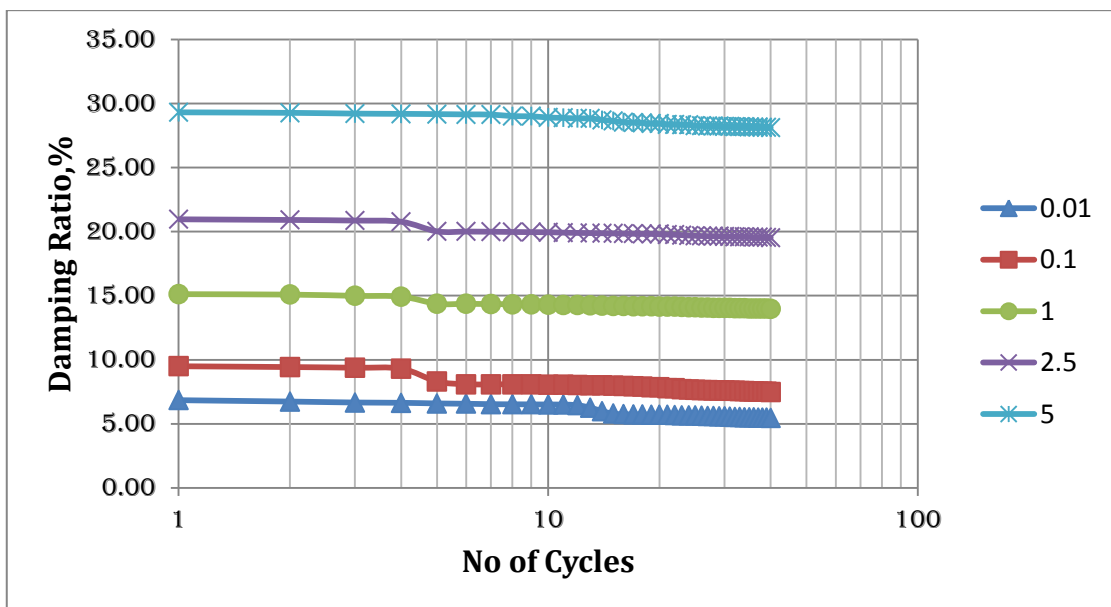


Figure H-4: Effect of number of cycles on shear modulus value for Test Pit 4 under axial stress of 200 kPa

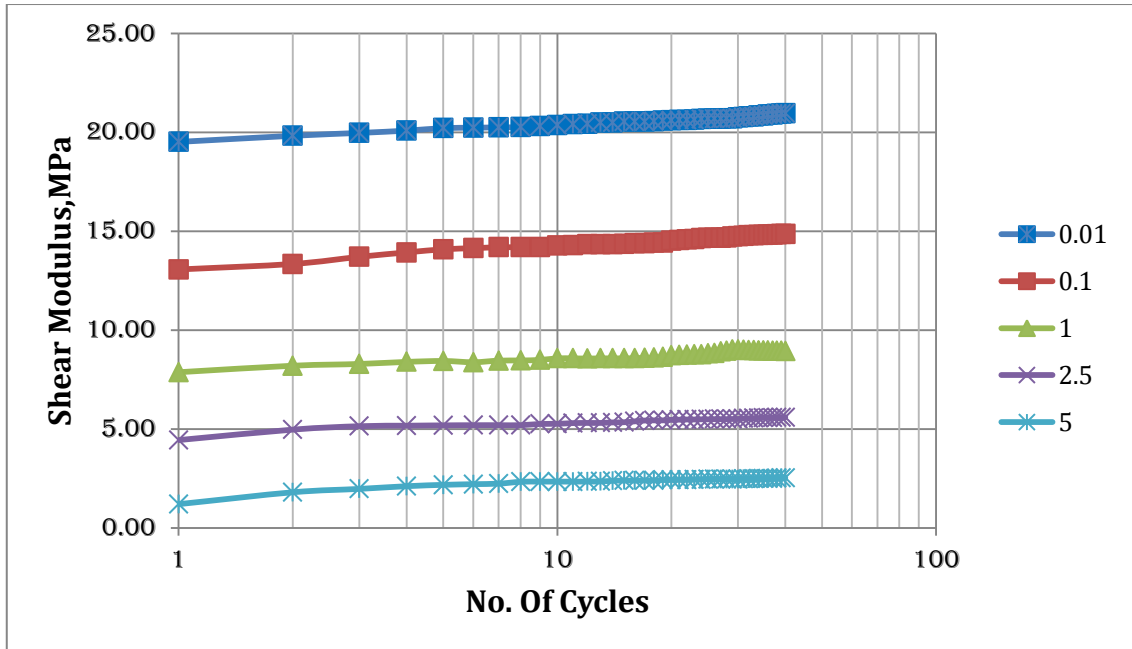


Figure H-5: Effect of number of cycles on shear modulus value for Test Pit 4 under axial stress of 400 kPa

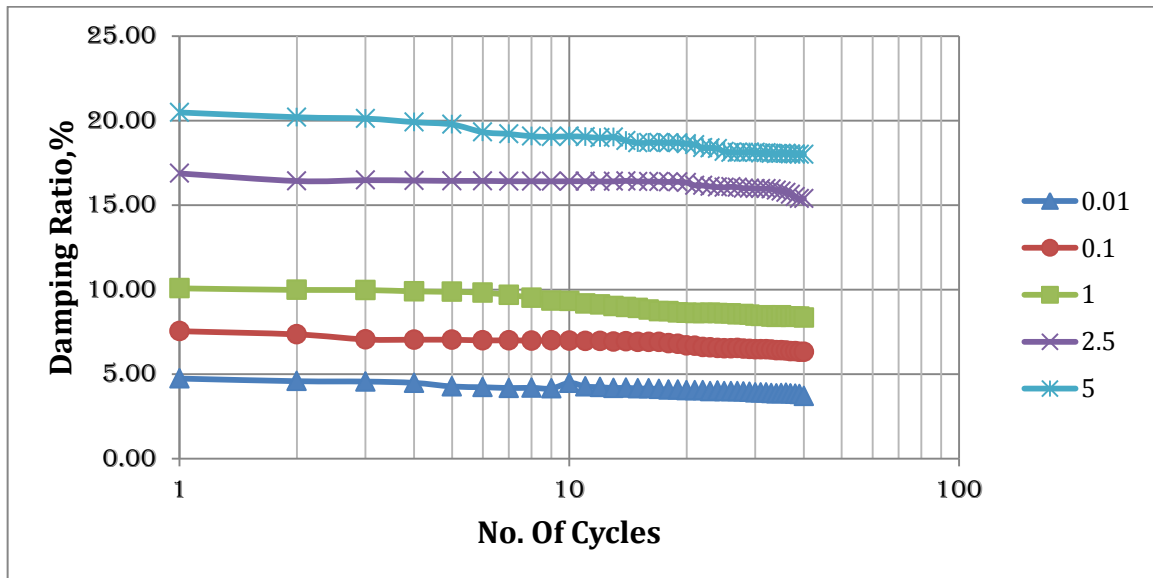


Figure H-6: Effect of number of cycles on damping ratio value for Test Pit 4 under axial stress of 400 kPa

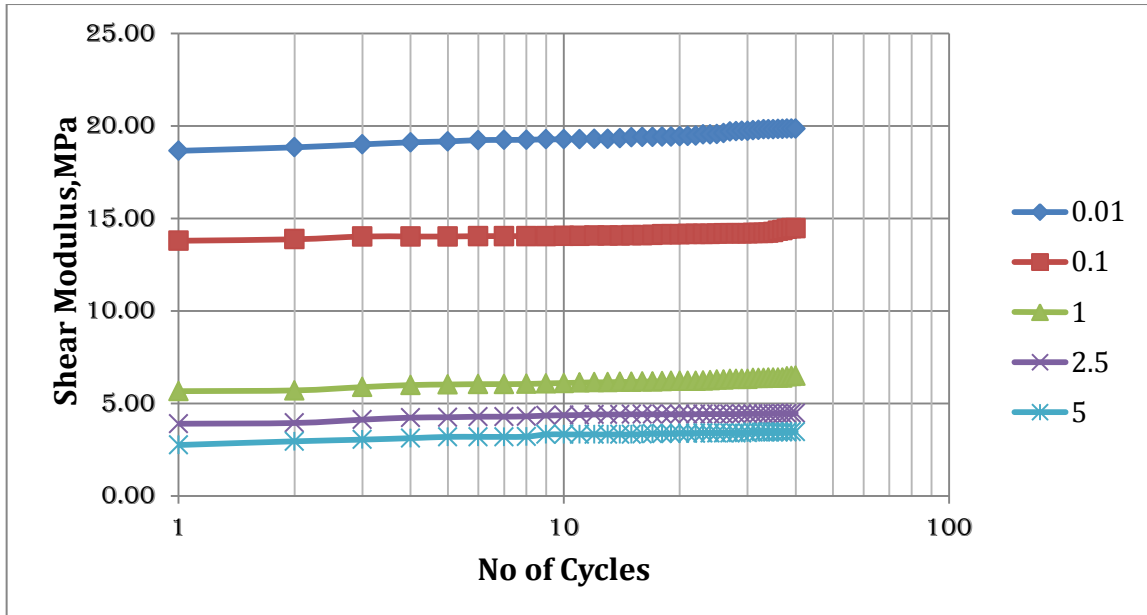


Figure H-7: Effect of number of cycles on shear modulus value for Test Pit 5 under axial stress of 100 kPa

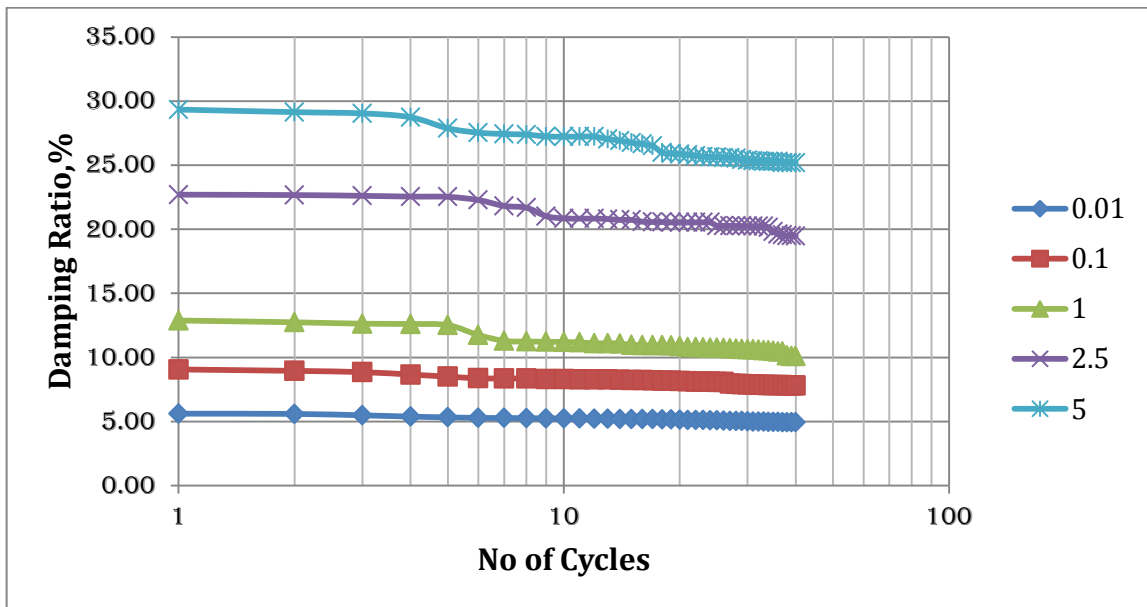


Figure H-8: Effect of number of cycles on shear modulus value for Test Pit 5 under axial stress of 100 kPa

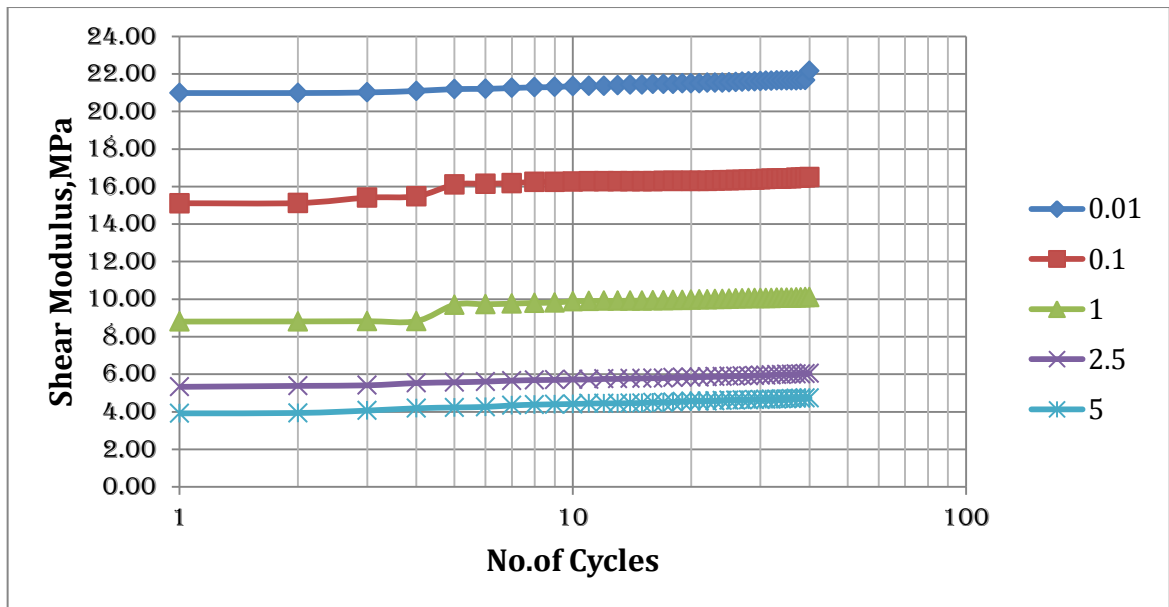


Figure H-9: Effect of number of cycles on shear modulus value for Test Pit 5 under axial stress of 200 kPa

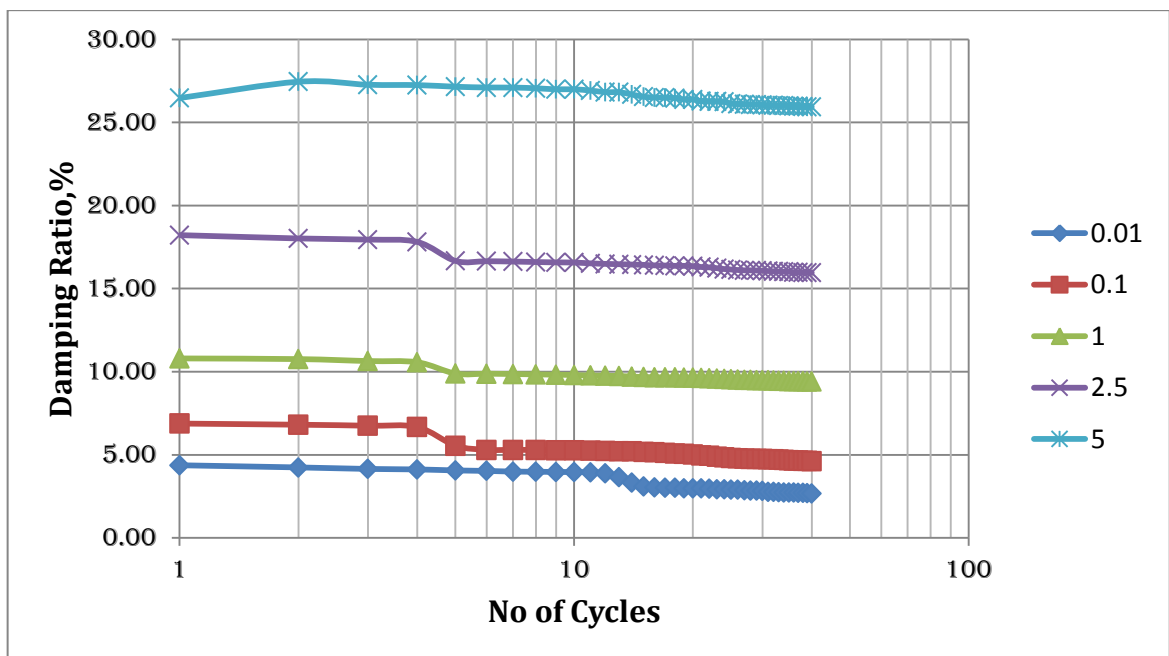


Figure H-10: Effect of number of cycles on damping ratio value for Test Pit 5 under axial stress of 200 kPa

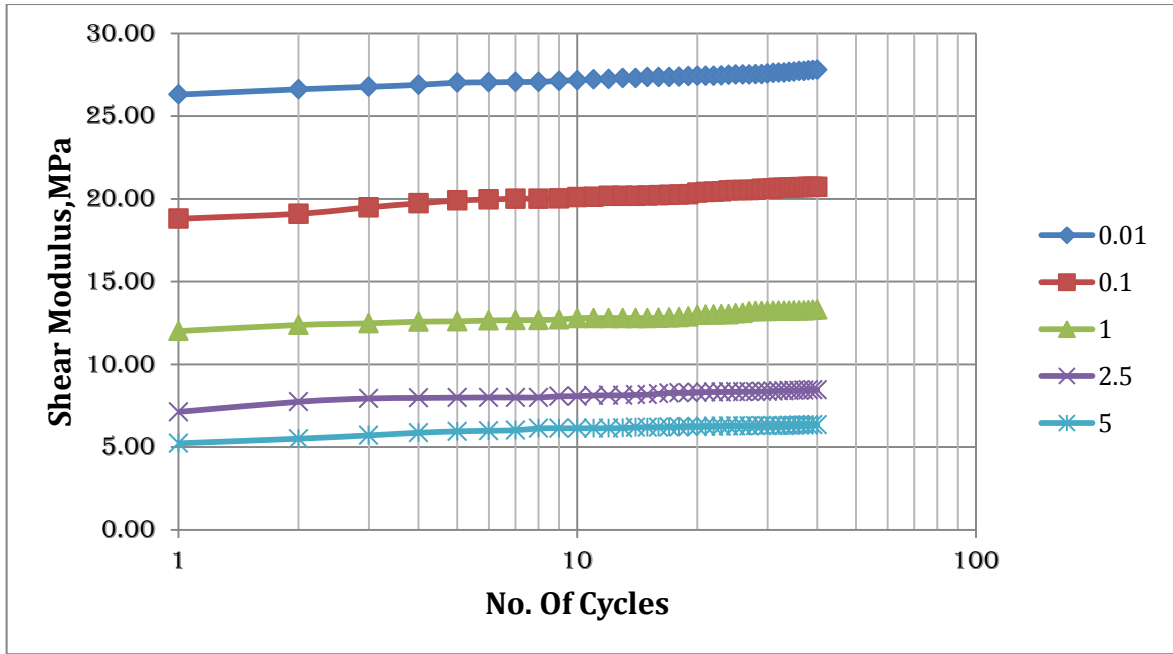


Figure H-11: Effect of number of cycles on Shear modulus value for Test Pit 5 under axial stress of 400 kPa

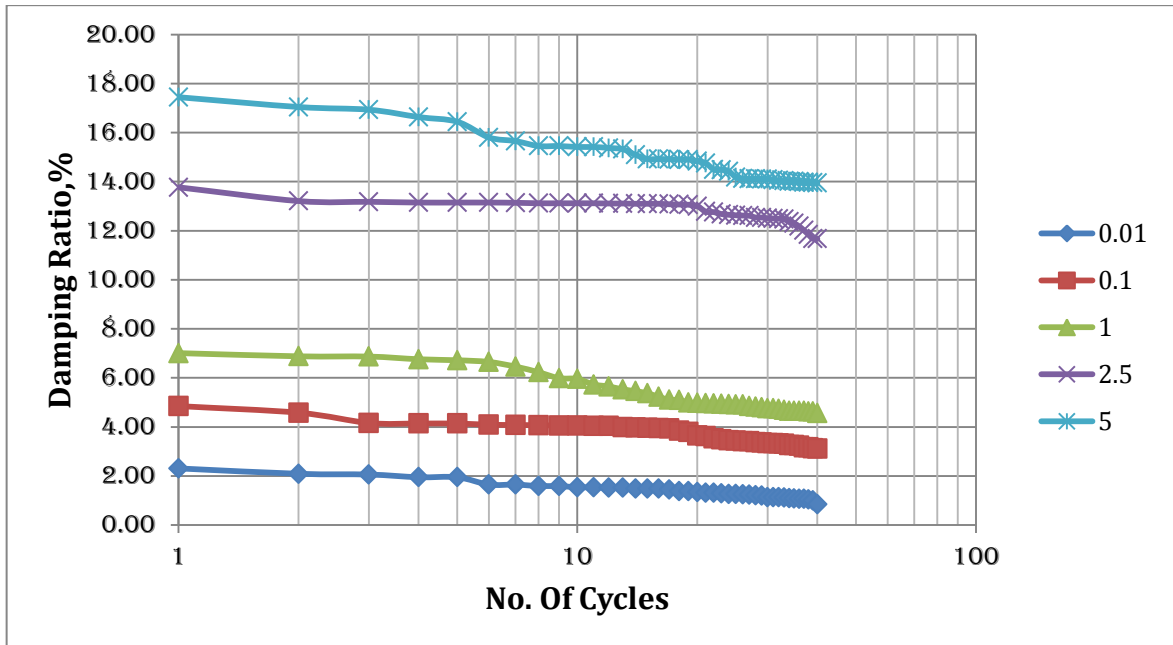


Figure H-12: Effect of number of cycles on damping ratio value for Test Pit 5 under axial stress of 400 kPa

Appendix I: Hysteresis loop

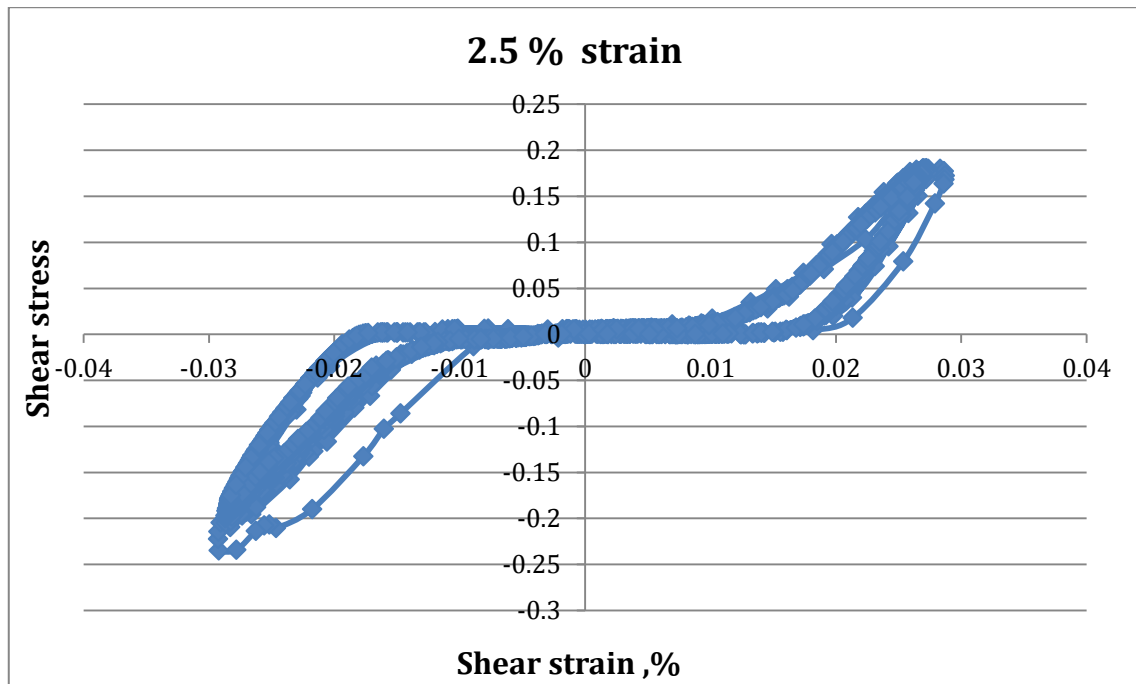


Figure I-1: Hysteresis loop for Test Pit 1 under axial stress of 100 kPa, (2.5 % Strain)

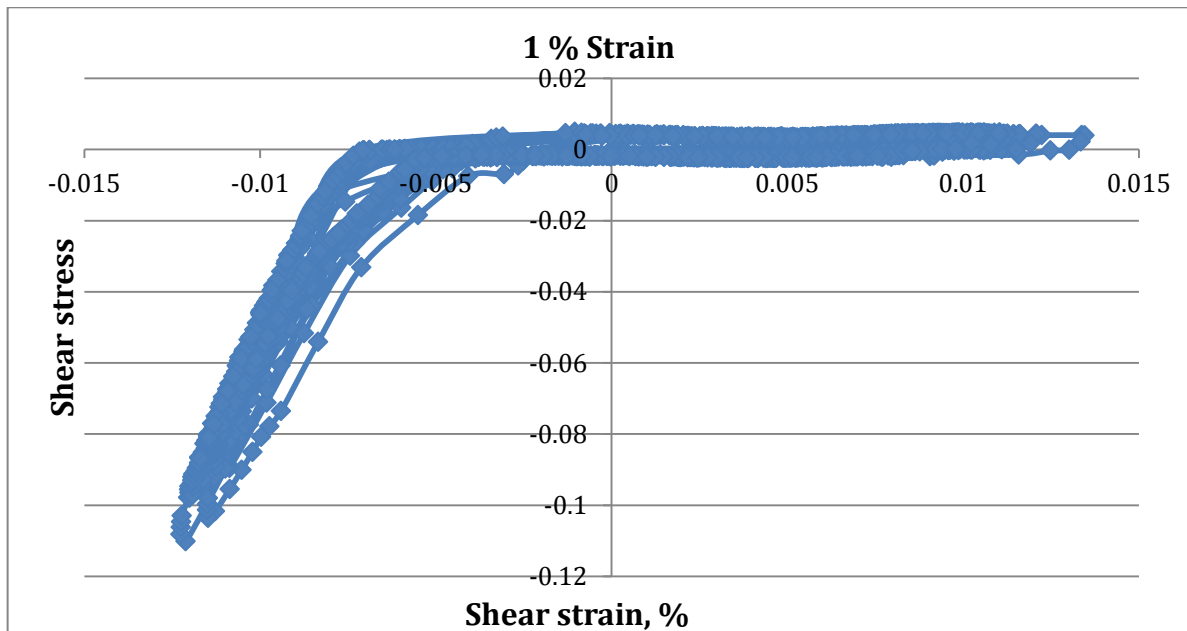


Figure I-2: Hysteresis loop for Test Pit 1 under axial stress of 100 kPa, (1 % Strain)

**Appendix J: Pictures**

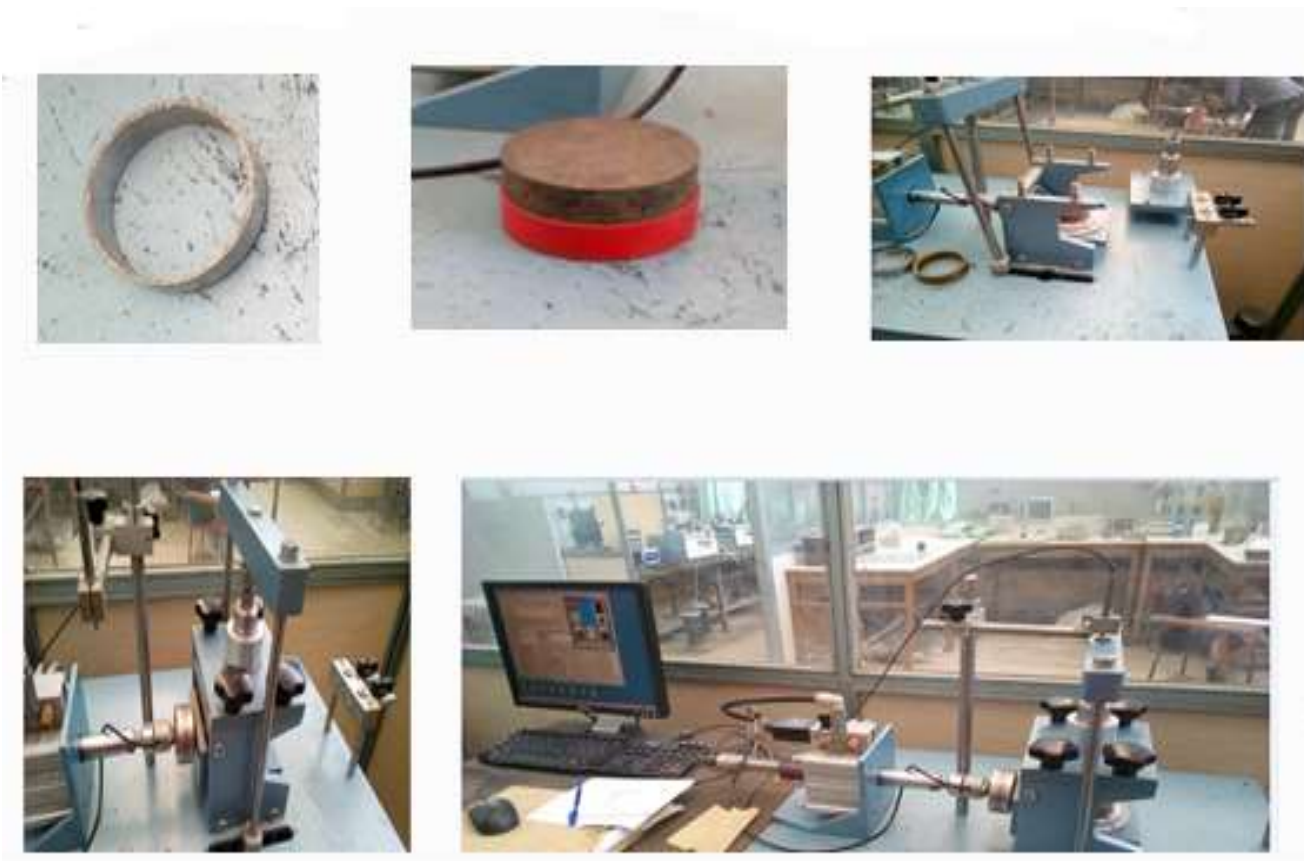


Figure J-1: Sample preparation and equipment set up



Figure J-2: Close up view of the apparatus